İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

COMPARISON OF OBSERVED STRUCTURAL DAMAGES AND CODE GIVEN STRUCTURAL PERFORMANCE LIMITS

M.Sc. Thesis by
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Department : Civil Engineering

Programme : Structural Engineering

JUNE 2011

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JUNE 2011

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

YÖNETMELİKLERDE VERİLEN YAPISAL DEPREM PERFORMANS LİMİTLERİNİN GÖZLEMLENEN HASARLAR İLE KARŞILAŞTIRILMASI

YÜKSEK LİSANS TEZİ

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HAZİRAN 2011

To my beloved mother,

FOREWORD

This study was performed under the supervision of the Prof. Dr. Alper İLKİ. I would like to express my sincere thanks and appreciations for his invaluable support, guidance, encouragement, criticisms and insights throughout this study. It was a great honor and pleasure to work with him.

I would like to thank M.Sc. Civil Engineer Bülent DEVECİ and Özgür TUNCER, patiently checked my calculations and supported my research. And also I would like to thank Molecular Biologist and Geneticist Nazlı Deniz KORKMAZ because of her supportings during whole this study.

I also would like to express my deepest thanks to my parents for the support, friendship, encouragement, and understanding that they have provided for me throughout my life.

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Emre EKİCİ

(Civil Engineer)

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ABBREVIATIONS

TSC	**:** Specification for Structures to be Built in Disaster Areas in Turkey, 2007
Eurocode	**:** Eurocode 8: Design of Structures for Earthquake Resistance, Part-3: Assessment and retrofitting of buildings
ASCE	**:** ASCE/SEI 41-06: Seismic Rehabilitation Standard (Update to ASCE/SEI Concrete Provisions)
PEER	**:** Pacific Earthquake Engineering Research Center
X-Tract	**:** Cross Sectional Analysis of Structural Components

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A,	cross sectional area of section;
A_g,	croos sectional area of core;
A_v,	cross sectional are of transverse reinforcement;
D,	diameter of circular columns;
D_o,	diameter of equivalent cross section of circular columns;
L,	length of columns;
L_P,	plastic hinge length;
L_{vi},	shear span at member end;
P,	axial load;
S,	spacing of transverse reinforcement;
b_w,	the length of transverse reinforcement for one leg;
b_x,	the dimension of section in x-x direction;
b_y,	the dimension of section in y-y direction;
f_c,	compressive strength of concrete;
f_{cc},	compressive strength of confined concrete;
f_{co},	compressive strength of unconfined concrete;
f_c',	compressive strength of concrete for cylinder specimens;
f_{su},	tensile strength of steel reinforcement;
f_{sy},	yielding strength of steel reinforcement;
f_{yw},	yielding strength of transverse reinforcement;
h,	depth of cross section;
α,	confinement effectiveness factor;
γ_{el},	importance factor of member;
ε_c,	concrete strain;
ε_{cu},	concrete ultimate strain;
ε_s,	steel strain;
ε_{sh},	steel strain at strain hardening;
ε_{su},	steel ultimate strain;
θ,	chord rotation;
θ_{DL},	chord rotation for damage limit;
θ_i,	chord rotation at i-point;
θ_{NC},	chord rotation for near collapse damage;
θ_p,	plastic chord rotation;
θ_{SD},	chord rotation for significant damage;
θ_{um},	ultimate chord rotation;
θ_y,	yielding chord rotation;
ν,	axial load ratio;
ρ,	total transverse reinforcement ratio;
ρ_x,	transverse reinforcement ratio in x-x direction;
ρ_y,	transverse reinforcement ratio in y-y direction;
ϕ_p,	plastic curvature;
ϕ_t,	total curvature;
ϕ_y,	yielding curvature;

Δ, displacement of member;

Δ_p, plastic displacement of member;

Δ_y, yielding displacement of member;

COMPARISON OF OBSERVED STRUCTURAL DAMAGES AND CODE GIVEN STRUCTURAL PERFORMANCE LIMITS

SUMMARY

Recently, the performance limits of structures and their members has become one of the popular research topics of non-linear structural analysis. Non-linear structural analysis provides more economical structures and also safety assessments for existing structures.

In structural analysis, non-linear analysis is more preferable more than linear analysis because of more realistic assessments. However, large variations in structures, structural members and characteristics of these members and also different approaches of structural codes make non-linear structural analysis argumentative.

In this thesis, Turkish Seismic Design Code (DBYBHY 2007), Eurocode 8 and ASCE/SEI 41-06 are compared with approaches of seismic performance assessments of existing structures.

Then comparison of these codes, the general information about propertis of reinforced concrete columns and test results given from PEER (Pasific Earthquake Engineering Research Center) database. And also the damages and displacements of rectancular and circular specimens are compared with the corresponding given limits in the codes mentioned above.

In conclusion, the estimations of the methods given in the codes are compared with each as well as the experimental results. This study has pointed that the performance limits given in the codes may significantly differ and also may conflict with experimental results.

YÖNETMELİKLERDE VERİLEN YAPI PERFORMANS LİMİTLERİNİN GÖZLEMLENEN YAPISAL HASARLAR İLE KARŞILAŞTIRILMASI

ÖZET

Son yıllarda, yeni inşaa edilecek yapıların ve bu yapıyı oluşturan elemanların deprem performans sınırlarının belirlenmesi ve değerlendirilmesi çok popüler bir araştırma konusu haline gelmiştir. Doğrusal olmayan hesap yöntemleri yeni yapılacak binalar için daha ekonomik, mevcut binalar için ise çok daha güvenli değerlendirme olanakları sunmaktadır.

Yapısal analiz yöntemleri içerisinde doğrusal hesap yöntemlerinden daha çok doğrusal olmayan hesap yöntemlerinin tercih ediliyor olmasının nedenlerinden bir tanesi de yapı ve yapı elemanlarının davranışlarında gerçeğe daha yakın sonuçlar bulunabilmesidir. Bununla birlikte, her bir farklı yapı için ve bu yapıları oluşturan elemanların karakteristik özelliklerinde ortaya çıkan değişkenlerin fazla olmasının yanına her yönetmeliğin bu doğrusal olmayan hesap yöntemlerine olan yaklaşımının faklı olması eklenince bu hesap yöntemleri tartışılabilir duruma gelmektedir.

Bu tez çalışmasında, mevcut yapı ve yapı elemanlarının deprem performanslarının belirmesinde izlenen yolları ve analiz sonuçları; Deprem Bölgelerinde Yapılacak Yapılar Hakkında Yönetmelik DBYBHY 2007, Eurocode 8 ve ASCE/SEI 41 yönetmelikleri dikkate alınarak karşılaştırılmalı olarak incelenmiştir.

Bu karşılaştırmanın sonrasında, tez çalışmasında kullanılan numuler için genel bilgiler ve bu numune deney sonuçlarının alındığı PEER (Pasific Earthquake Engineering Research Center) hakkında bilgiler verilmiştir. Ayrıca yukarıda belirtilen yönetmeliklere göre her bir numune için hesaplanan deprem performans limitleri deney sonucu ortaya çıkan hasar durumları ile tablolar halinde kıyaslanmıştır.

Sonuç olarak, her bir numune için yönetmeliklere göre bulunan hasar sınırları deney sonuçları ile kıyaslanmıştır ve bu çalışma göstermiştir ki yönetmeliklerde verilen hasar sınırları hem birbileri ile hem de deney sonuçları ile farklılıklar gösterebilmektedir.

1. INTRODUCTION

An earthquake is ground shaking caused by a sudden movement of rock in the Earth's crust. Such movements occur along faults, which are thin zones of crushed rock separating blocks of crust. When one block suddenly slips and moves relative to the other along a fault, the energy released creates vibrations called seismic waves that radiate up through the crust to the Earth's surface, causing the ground to shake. (Url-1, 2011). The stronger ground shaking generated in such events is unlikely to affect people directly (other than by startling or frightening them). It is what these ground motions can do to the natural and man-made environments around us that can significantly affect us by endangering our lives, property, and livelihoods.

Turkey is an earthquake-prone country has a long history of natural hazards and disasters. Approximately 96 percent of the land containing 66 percent of the active faults is affected by earthquake hazards and 98 percent of its population lives in these regions. The Marmara region includes 11 large cities with populations of more than one million and 75 percent of the country's largest industrial complexes. In last 58 years, 58202 people have been lost their lives, 122096 people have been injured and approximately 411465 buildings have been collapsed and damaged strongly (Url-2, 2011).

After all these seismic hazards, earthquake-resistance design of strucures and seismic assessment and rehabilitation of existing buildings have become very important topic in structural engineering. Therefore, the realibity of approaches of current seismic regulations is very significant for the structural design and assessments of the existing structures.

During the evaluations of structures, the performance of building and damages can be occurred in seismic loads should be determined as close as possible to reality. The realistic definitions of the behaviors of structure and structural members, provide the safety and economical design and also this is so distinctive for the retrofit and seismic assessments of existing buildings after the earthquake. While buildings are usually designed for seismic resistance using elastic analysis, most will experience significant inelastic deformations under large earthquakes. Modern performance-based design methods require ways to determine the realistic behavior of structures under such conditions. Enabled by advancements in computing technologies and available test data, nonlinear analyses provide the means for calculating structural response beyond the elastic range, including strength and stiffness deterioration associated with inelastic material behavior and largedisplacements. As such, nonlinear analysis can play an important role in the design of new and existing buildings. However, the variety of structures and structural members, many variables such as material and geometric properties usually cause unrealistic results in performance analysis of structures with these design methods.

1.1 Purpose of the Thesis

In this thesis study; the general information for determining the performance limits of existing buildings according to Turkish Seismic Code (TSD 2007), Eurocode (EN 1998, 2005) and ASCE 41-06 with Update 2007 is given firstly.

The damage limitations, analysis methods to determine unit deformations, material models and section deformation capacities are studied within these mentioned seismic codes. And also all detailed information can be found in related master thesis (Işıltan, 2010).

When these limits are been determining, all geometric and material properties with loading information of specimens are necessary to model them in X-Tract program. Therefore, the general information for specimens used in thesis study is given according reported values from PEER database.

These limits are determined for all seismic codes and then these calculated values were compared with observed damages by the researchers from PEER. M. Sc. Özgecan Işıltan has been done this study in his master thesis with 33 rectangular columns and this thesis study is an extension of his study with 19 circular and 33 rectangular columns. And also the transverse reinforcement ratio given by PEER is clarified to adapt X-Tract program.

With thesis study, the performance assessments of the codes can differ and contradict with the experimental results.

2. COMPARATIVE EVAULATION OF SEISMIC CODES

In this section, the structural seismic performance limits of existing buildings will be evaluated comparatively according to Specification for Structures To Be Built in Disaster Areas in Turkey (DBYBHY, 2007), Eurocode 8: Design of structures for earthquake resistance and Seismic Rehabilitation Standard (ASCE/SEI 41-Update 2007).

General principles of Turkish Seismic Code 2007 and Eurocode 8, are given in related master thesis (Işıltan, 2010) and these principles can be listed below;

- The scope of codes.
- The definition of knowledge levels for existing buildings.
- The identification of knowledge levels for existing buildings.
- The methods of linear elastic and non-linear plastic analysis used in codes.
- The performance levels of existing buildings.

According to these principles, data collection from buildings is the first stage to determine the assessment of structural performance of buildings. This data can be stated as the details and sizes of the elements to be used in determining the capacities of the elements of the supporting systems of the existing buildings. The information regarding the geometry and material characteristics of the supporting systems will be achieved from the projects and reports of such buildings, from observations and measurements to be carried out on the building, and from trials performed on the material samples taken from the building.

In the light of these information, the limit states for seismic performance given in the seismic codes will be compared with each other as well as the experimental results.

2.1 Limit States for Structural Damages Proposed by Turkish Seismic Code 07

The limit states of structural performance levels are stated in Chapter 7 – Evaluation and Retrofitting of the Existing Buildings of Turkish Seismic Code 2007. The rules of calculation to be used in the assessment of performances of the existing buildings in earthquake zones under the impact of an earthquake, principles to be followed in decisions of strengthening is made are defined in this section of Turkish Seismic Code 2007.

2.1.1 Damage limits in cross sections

There limit conditions have been defined for ductile elements on the cross section. These are Minimum Damage Limit (MN), Safety Limit (GV) and Collapsing Limit (GÇ). Minimum damage limit defines the beginning of the behavior beyond elasticity, safety limit defines the limit of the behavior beyond elasticity that the section is capable of safely ensuring the strength, and collapsing limit defines the limit of the behavior before collapsing. This classification does not apply to elements damaged in a brittle condition.

Elements that the damages with critical sections do not reach MN are within the Minimum Damage Region, those in-between MN and GV(SF) are within Significant Damage Region, those in-between GV(SF) and GÇ(CL) are in Extreme Damage Region, and those going beyond GÇ(CL) are within Collapsing Region (Figure 2.1).

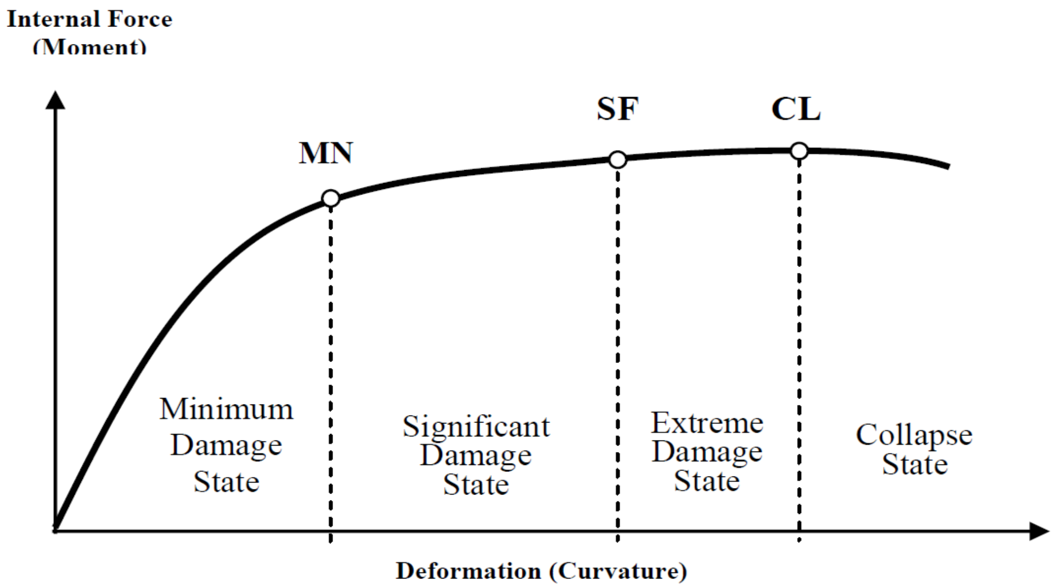

Figure 2.1 : Internal Force versus Deformation Curve.

2.1.2 Determining the unit deformation demands

The plastic bending demand dependent on the θ_p plastic rotation demand that shall be obtained in any section as a result of the repulsion analysis or obtained as a output information onto the calculation conducted within the scope of time definition shall be calculated as follows;

$$\varphi_p = \frac{\theta_p}{L_p} \tag{2.1}$$

$$L_p = 0.50xh \tag{2.2}$$

The plastic hinge length of cross section is taken according to the Equation (2.2) and the total bending demand ϕ_t of the section shall be obtained adding the ϕ_y equivalent yield bending that is defined with the two-line momentum-bending relationship obtained from the analysis conducted under the axial force demand of the section by means of using a reinforcement steel model that as well considers the strain hardening together with a concrete model chosen in accordance with the aim to the . ϕ_p plastic bending demand defined with the Equation (2.1):

$$\varphi_t = \varphi_y + \varphi_p \tag{2.3}$$

All calculations of structural performance limits proposed by Turkish Seismic Code 2007, have been done according this given general principles. The calculation procedure has shown in Figure 2.2.

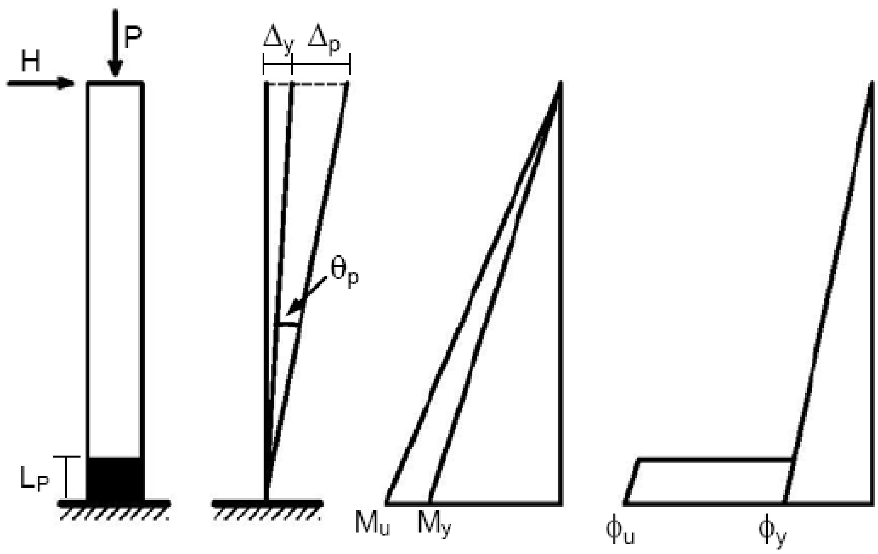

Figure 2.2 : Plastic-Hinge Analysis (Özmen et al., 2007)

2.1.3 Material parameters for moment-curvature analysis

On the performance evaluation with methods given in Section 2.1.2, stress-strain curves for unconfined and confined concrete, is defined according to Mander et al. (1988) models. All information about this material model can be found in related master thesis (Işıltan, 2010).

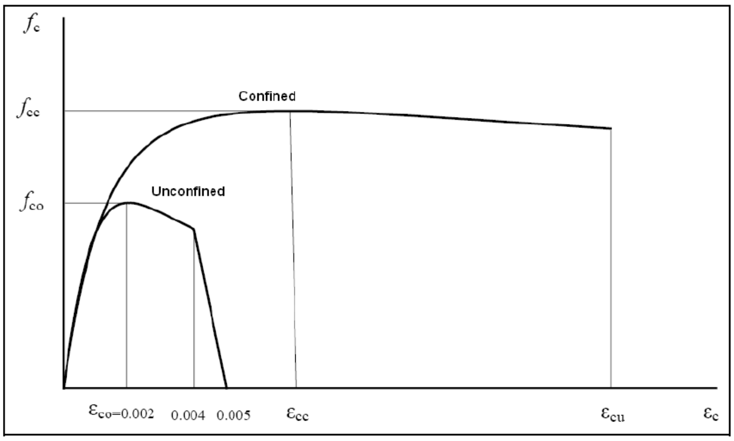

Figure 2.3 : Stress-strain relations for confined and unconfined concrete - Mander et al. (1988).

The material models for unconfined and confined concrete in Turkish Seismic Code 2007, only differs from Mander et al. material models (1988) for maximum strain value of confined concrete. This value is given below;

$$\varepsilon_{cu} = 0.004 + \frac{1.4\rho_s f_{yw}\varepsilon_{su}}{f_{cc}} \tag{2.4}$$

On the performance evaluation with methods given in Section 2.1.2, stress-strain curves for reinforcement steel, are given according to steel reinforcement quality in S220 and S420 in Table 2.1.

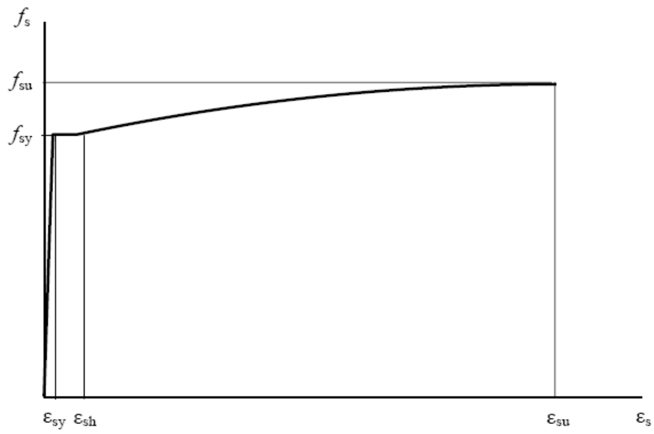

Figure 2.4 : Stress-strain relations for steel reinforcement (TSC, 2007)

Table 2.1: Information concerning reinforcement steel with quality S220 and S420 (TSC, 2007).

Quality	fsy (Mpa)	ε_{sy}	ε_{sh}	ε_{su}	f_{su} (Mpa)
S220	220	0.0011	0.011	0.16	275
S420	420	0.0021	0.008	0.10	550

In the scope of this thesis study, the reinforcement properties are very variable and their characteristics are not similar to S220 and S420 reinforcement steel. In the moment-curvature analysis of cross sections, the strain at the onset of strain hardening and failure strain of reinforcement have been assumed as given below;

$$\varepsilon_{sh} = 0.04 \quad \textbf{(2.5)}$$

$$\varepsilon_{su} = 0.15 \quad \textbf{(2.6)}$$

The reinforcement steel of all specimens, have been modeled according to these values in X-Tract analysis program.

2.1.4 Section deformation capacities of reinforced concrete components

The seismic demands obtained in accordance with section 2.1.2 in terms of unit deformation demands for concrete or reinforcement steel shall be compared with the unit deformation capacities given below so as to determine the performance of the load-bearing systems at sectional level.

The upper bounds (capacity) of deformation for different sectional damage thresholds for the ductile load-bearing system components that undergo plastic deformations are defined below:

For Minimum Sectional Damage Boundary (MN), upper bounds of the concrete unit pressure deformation in the outmost fiber of the section and the reinforcement steel unit deformation demands:

$$(\varepsilon_{cu})_{MN} = 0.0035 \quad \textbf{(2.7)}$$

$$(\varepsilon_{s})_{MN} = 0.010 \quad \textbf{(2.8)}$$

For Section Security Bound (GV), upper bounds of the concrete unit pressure deformation in the outmost fiber of hoop and the reinforcement steel unit deformation demands:

$$(\varepsilon_{cu})_{GV} = 0.0035 + 0.01(\rho_s / \rho_{sm}) \leq 0.0135 \quad \textbf{(2.9)}$$

$$(\varepsilon_{s})_{GV} = 0.040 \quad \textbf{(2.10)}$$

For Section Collapse Bound (GÇ), upper bounds of the concrete unit pressure deformation in the outmost fiber of hoop and the reinforcement steel unit deformation demands:

$$(\varepsilon_{cu})_{GÇ} = 0.0040 + 0.013(\rho_s / \rho_{sm}) \leq 0.0180 \quad \textbf{(2.11)}$$

$$(\varepsilon_s)_{GÇ} = 0.060 \quad \textbf{(2.12)}$$

In these equations; ε_{cu}, the compressive strain of concrete; ε_s, the strain of reinforcement steel; ρ_s, current steel reinforcing ratio of special earthquake hoops and crossties in cross section; ρ_{sm}, the required steel reinforcing ratio of special earthquake hoops and crossties in cross section.

2.2 Limit States for Structural Damages Proposed by Eurocode 8

The limit states of structural performance levels are stated in Part 3: Assessment and retrofitting of buildings of Eurocode 8. The scope of this code is as follows:

- To provide criteria for the evaluation of the seismic performance of existing individual building structures.
- To describe the approach in selecting necessary corrective measures
- To set forth criteria for the design of retrofitting measures (i.e. conception, structural analysis including intervention measures, final dimensioning of structural parts and their connections to existing structural elements).

2.2.1 Damage limits in cross sections

The fundamental requirements refer to the state of damage in the structure, herein defined through three Limit States (LS), namely Near Collapse (NC), Significant Damage (SD), and Damage Limitation (DL). These Limit States shall be characterized as follows:

Limit States of Near Collapse (NC). The structure is heavily damaged, with low residual lateral strength and stiffness, although vertical elements are still capable of sustaining vertical loads. Most non-structural components have collapsed. Large permanent drifts are present. The structure is near collapse and would probably not survive another earthquake, even of moderate intensity.

Limit States of Significant Damage (SD). The structure is significantly damaged, with some residual lateral strength and stiffness, and vertical elements are capable of sustaining vertical loads. Non-structural components are damaged, although partitions and infills have not failed out-of-plane.

Moderate permanent drifts are present. The structure can sustain after-shocks of moderate intensity. The structure is likely to be uneconomic to repair.

Limit States of Damage Limitation (DL). The structure is only lightly damaged, with structural elements prevented from significant yielding and retaining their strength and stiffness properties. Non-structural components, such as partitions and infills, may show distributed cracking, but the damage could be economically repaired. Permanent drifts are negligible. The structure does not need any repair measures.

2.2.2 Determining the unit deformation demands

Chord rotation is stated as the deformation capacity of reinforced concrete members. According to Eurocode 8 chord rotation is the angle between the tangent to the axis at yielding end and the chord rotating at that end with the end of shear span (Lv =M/V= moment /shear at the end section). Other definition of chord rotation is equal to the element drift ratio, the deflection at the end of the shear span with respect to the tangent to the axis at the yielding end, divided by the shear span.

$$\theta_i = \frac{\delta_i}{L_{vi}} = \left| \frac{\Delta}{L} - \phi_i \right| \quad \textbf{(2.13)}$$

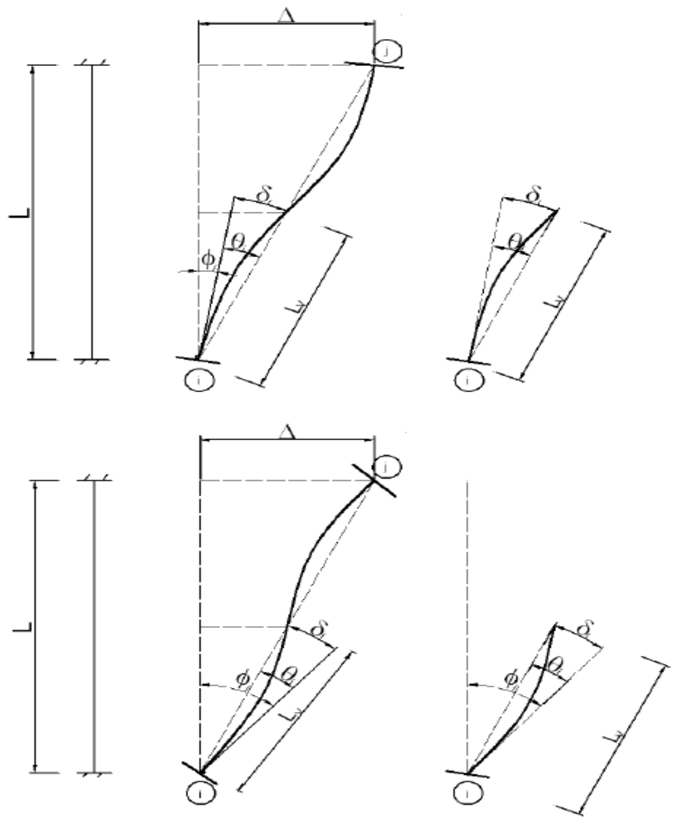

Figure 2.5 : Definition of chord rotation (Özal, 2005).

In Equation 1.13, θ_i, chord rotation; δ_i, deflection occurred because of difference of chord rotation and rotation of bottom joint (i); Δ, the deflection of top joint (j); L, the height of the column; ϕ_i, rotation of bottom joint (i). The calculations of chord rotation according to Eurocode 8, are based on empirical expressions and there are many variables in these expressions.

2.2.3 Section deformation capacities of reinforced concrete components

Limit state of damage limitation (DL)

The capacity for this limit state used in the verifications is the yielding bending moment under the design value of the axial load.

In case the verification is carried out in terms of deformations the corresponding capacity is given by the chord rotation at yielding θ_y, evaluated as:

For beams and columns:

$$\theta_y = \phi_y \frac{L_v + \alpha_v z}{3} + 0.00135\left(1 + 1.5\frac{h}{L_v}\right) + \frac{\varepsilon_y}{d - d'}\frac{d_b f_y}{6\sqrt{f_c}} \qquad \textbf{(2.14)}$$

Or from the alternative expressions for beams and columns:

$$\theta_y = \phi_y \frac{L_v + \alpha_v z}{3} + 0.0013\left(1 + 1.5\frac{h}{L_v}\right) + 0.13\phi_y \frac{d_b f_y}{\sqrt{f_c}} \qquad \textbf{(2.15)}$$

In this equation; ϕ_y, the yield curvature of the end section; $\alpha_v z$, the tension shift of the bending moment diagram (EN 1992-1-1: 2004, 9.2.1.3(2)); f_y, the steel yield stress; f_c, the concrete strength; ε_y, equal to f_y/E_s; d and d', the depths to the tension and compression reinforcement; d_b, the diameter of the tension reinforcement.

Limit State of Significant Damage (SD)

The chord rotation for significant damage (SD) should be equal or less than 75% ($\theta_{SD} \leq 3/4\theta_{um}$) of the chord rotation calculated for limit state of near collapse (NC).

Limit State of Near Collapse (NC)

The limit chord rotation for near collapse (NC) should be equal or less than the value of the total chord rotation capacity (elastic plus inelastic part) at ultimate ($\theta_{NC} \leq \theta_{um}$), θ_{um}, of concrete members under cyclic loading may be calculated from the following expression:

$$\theta_{um} = \frac{1}{\gamma_{el}} 0.016(0.3^{\nu}) \left[\frac{\max(0.01;\omega')}{\max(0.01;\omega)} f_c \right]^{0.225} \left(\frac{L_v}{h} \right)^{0.35} 25^{\left(\alpha\rho_{sx}\frac{f_{yw}}{f_c}\right)} (1.25^{100\rho_d}) \qquad \textbf{(2.16)}$$

where: γel, is equal to 1,5 for primary seismic elements and to 1,0 for secondary seismic; h, is the depth of cross-section; L_V = M/V, is the ratio moment/shear at the end section; ν, is equal to ratio of N/bhf_c; ω and ω´, is the mechanical reinforcement ratio of longitudinal reinforcement; f_c, is the concrete compressive strength (MPa); f_{yw}, is the stirrup yield strength (MPa); ρ_{sx}, is the ratio of transverse steel parallel to the direction x of loading; ρ_d, is the steel ratio of diagonal reinforcement; α, is the confinement effectiveness factor, that may be taken equal to:

$$\alpha = \left(1 - \frac{s_h}{2b_o}\right)\left(1 - \frac{s_h}{2h_o}\right)\left(1 - \frac{\Sigma b_i^2}{6h_o b_o}\right) \qquad \textbf{(2.17)}$$

In Equation 1.17: b_o and h_o, are the dimension of confined core to the centreline of the hoop; b_i, is the centerline spacing of longitudinal bars (indexed by i) laterally restrained by a stirrup corner or a cross-tie along the perimeter of the cross-section. These definitions can also be seen in Figure 2.6.

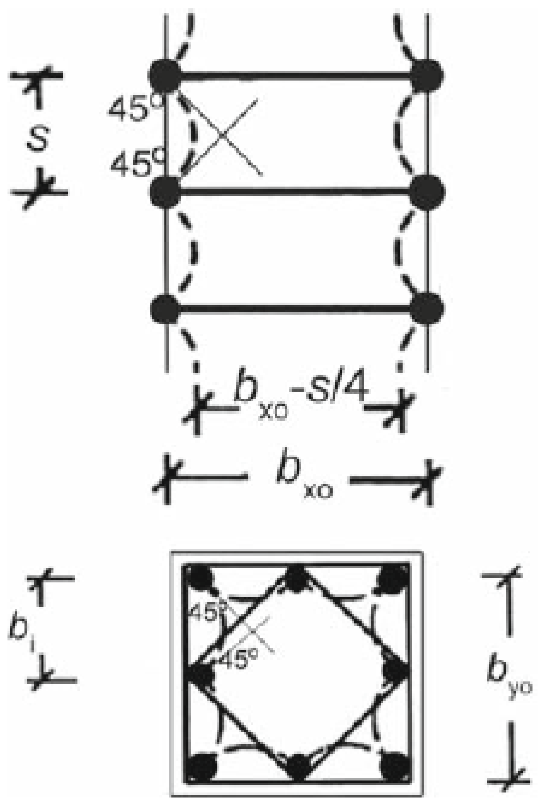

Figure 2.6 : Confined and unconfined parts over the cross-section and along a member with square section and multiple ties (Fardis, 2009).

The confinement effectiveness factor for spiral columns with circular hoops, are given below;

$$\alpha = \left(1 - \frac{s}{2D_o}\right)^2 \quad \textbf{(2.18)}$$

The confinement effectiveness factor for spiral columns with spiral transverse reinforcement, is given below;

$$\alpha = \left(1 - \frac{s}{4D_o}\right)^2 \quad \textbf{(2.19)}$$

where: D_o, is the centerline diameter of the hoop or spiral. The figure of definitions of Equation 2.18 and 2.19, is given below;

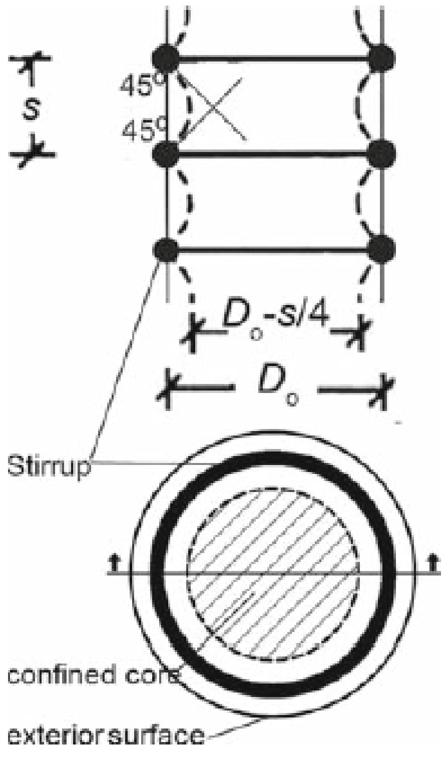

Figure 2.7 : Confined and unconfined parts over the cross-section and along a member with circular section and circular hoops (Fardis, 2009).

For the evaluation of the ultimate chord rotation capacity an alternative expression may be used:

$$\theta_{um} = \frac{1}{\gamma_{el}}\left(\theta_y + (\phi_u - \phi_y)\,L_{p1}\left(1 - \frac{0.5L_{p1}}{L_v}\right)\right) \quad \textbf{(2.20)}$$

In walls the value given by expression (1.16) is divided by 1,6. In members without detailing for earthquake resistance the values given by expression (1.16) is multiplied by 0,825. In members with smooth (plain) longitudinal bars without lapping in the vicinity of the end region where yielding is expected, the total chord rotation capacity may be taken equal to the value calculated in accordance with Equation (1.16) multiplied by 0,575.

2.2.4 The plastic hinge length used in calculations

The ultimate condition in terms of deformations is commonly defined conventionally, as described in Section 2.2.3 for the ultimate curvature. The ultimate chord rotation occurs at the same time as the ultimate curvature and is defined similarly. The most common model for the ultimate chord rotation at the member end (let's say A) where the moment is maximum (Fig. 3.32) uses the yield and ultimate curvatures at section A and assumes that at ultimate conditions the plastic part of the curvature is constant and equal to $\phi_u - \phi_y$ over a length Lpl next to the end section at A. This means that the real distribution of plastic curvatures, which is nearly triangular over the length of plastification lpl, is replaced by a uniform plastic curvature over a shorter length $L_{pl} \approx 0.5 l_{pl}$. L_{pl} is called "plastic hinge length" and is a conventional quantity (Fardis, 2009).

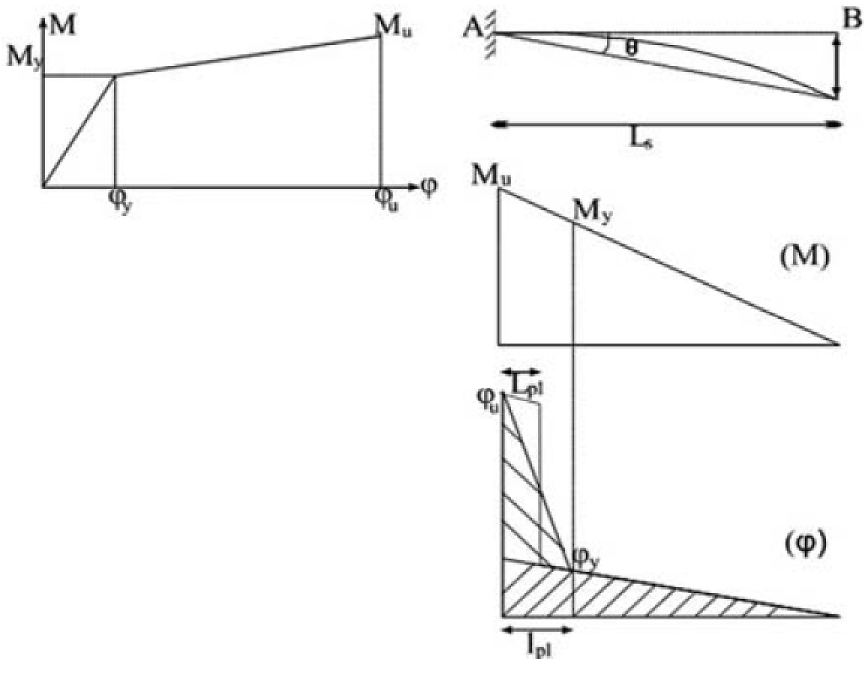

Figure 2.8 : Actual plastification length, l_{pl} and plastic hinge length L_{pl} in the shear span (Fardis, 2009).

There are two expressions evaluated here are those given in Annex A of Part 3 of Eurocode 8 for cyclic loading of members detailed for earthquake resistance:

- For members with detailing for earthquake resistance and without lapping of longitudinal bars in the vicinity of the section where yielding is expected, L_{pl} may be calculated from the following expression:

$$L_{pl} = 0.1L_v + 0.17h + 0.24\frac{d_{bL}f_y(MPa)}{\sqrt{f_c(MPa)}} \tag{2.21}$$

where h is the depth of the member and d_{bL} is the (mean) diameter of the tension reinforcement.

- For members with detailing for earthquake resistance and no lapping of longitudinal bars near the section where yielding is expected, Lpl may be calculated from the following expression:

$$L_{pl} = \frac{L_v}{30} + 0.20h + 0.11\frac{d_{bL}f_y(MPa)}{\sqrt{f_c(MPa)}} \tag{2.22}$$

If the confinement model in EN1992-1-1: 2004 3.1.9 is used for calculations of the ultimate curvature of the end section, ϕ_u, and the value of L_{pl} from Equation 2.21 is used in Equation 2.20 , then the factor γ_{el} therein may be taken equal to 2 for primary seismic and to 1.0 for secondary seismic elements.

In this thesis study, the confinement model given in Annex A of Part 3 of Eurocode 8 is used, together with Equation 2.22, then the value of the factor γ_{el} may be taken equal to 1.7 for primary seismic elements and to 1.0 for secondary seismic ones.

2.2.5 Material parameters for moment-curvature analysis

In this section, all material behavior of structural materials are given according to Eurocode 2: Design of concrete structures and Part 3: Assessment and retrofitting of buildings of Eurocode 8. In calculations of thesis study, the unconfined concrete model is taken according to Section 3.1.5 of Eurocode. The stress-strain relationship of unconfined concrete can be seen in Figure 2.9.

And material parameters are given in Table 2.5 based on Table 3.1 of EN1992-1-1. For confined concrete, confinement of concrete results in a modification of effective stress-strain relationship: higher strength and higher critical strains are achieved.

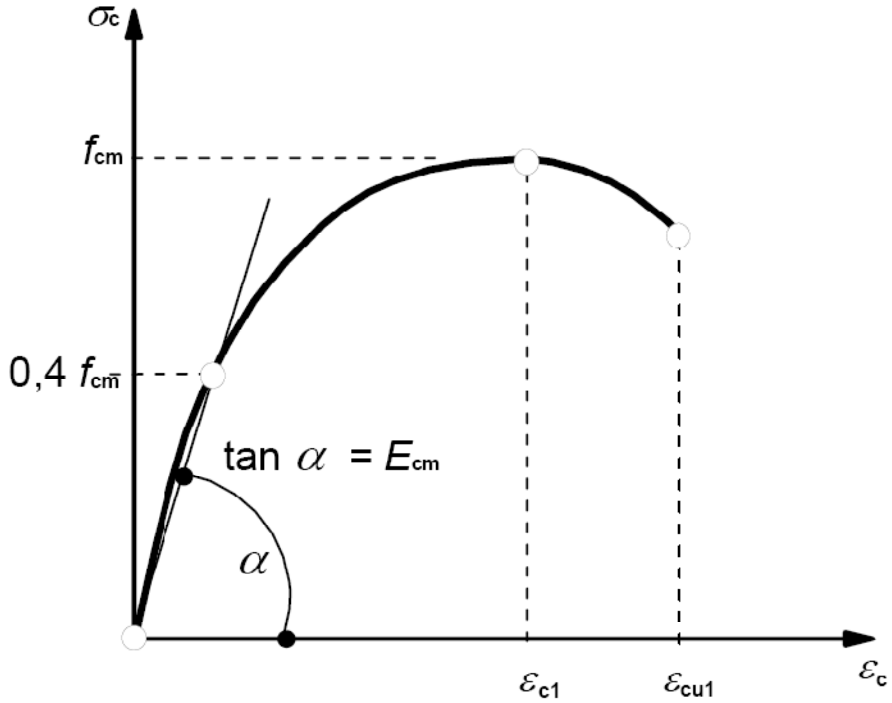

Figure 2.9 : Schematic representation of the stress-strain relation for structural analysis (EN1992-1-1, 2009).

Table 2.2: Strength and deformation characteristics of concrete (EN1992-1-1, 2004).

Strength classes for concrete									
f_{ck}(MPa)	12	16	20	25	30	35	40	45	50
f_{cm}(MPa)	20	24	28	33	38	43	48	53	68
E_{cm}(GPa)	27	29	30	31	33	34	35	36	37
ε_{c1}(%o)	1.80	1.90	2.00	2.10	2.20	2.25	2.30	2.40	2.45
ε_{cu1}(%o)					3.50				
ε_{c2}(%o)					2.00				
ε_{cu2}(%o)					3.50				

The other basic material characteristics may be considered as unaffected for design. In the absence of more precise data, the stress-strain relation shown in Figure 2.10 (compressive strain shown positive) may be used, with increased characteristic strength and strains according to:

- the strength of confined concrete is evaluated from;

$$f_{cc} = f_c\left[1+3.7\left(\frac{\alpha\rho_{sx}f_{yw}}{f_c}\right)^{0.86}\right] \quad \textbf{(2.23)}$$

- the strain at which the strength fcc takes place is taken to increase over the value εc2 of unconfined concrete as:

$$\varepsilon_{c2,c} = \varepsilon_{c2}\left[1+5\left(\frac{f_{cc}}{f_c}-1\right)\right] \quad \textbf{(2.24)}$$

- the ultimate strain of the extreme fibre of the compression zone is taken as:

$$\varepsilon_{cu2,c} = 0.004 + 0.5\varepsilon_{c2}\frac{\alpha\rho_{sx}f_{yw}}{f_{cc}} \quad \textbf{(2.25)}$$

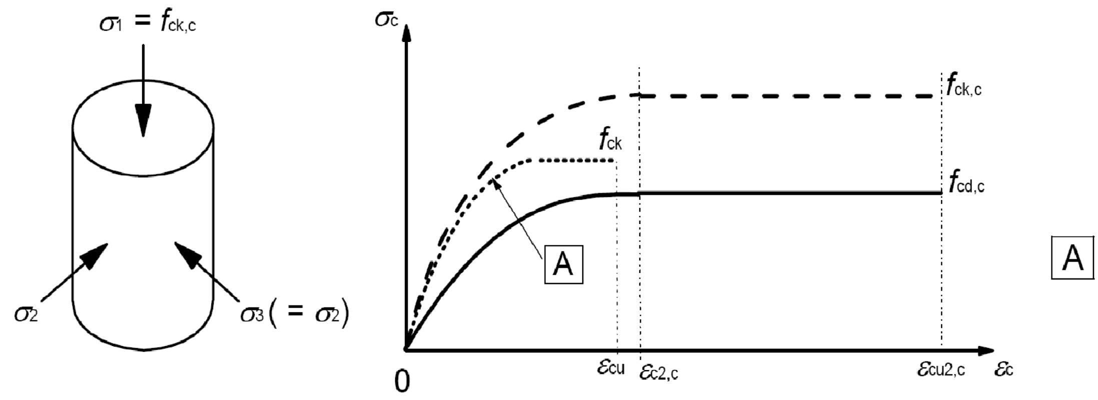

Figure 2.10 : Stress-strain relationship for confined concrete (EN1992-1-1, 2009).

2.3 Limit States for Structural Damages Proposed by ASCE/SEI 41 (2007)

ASCE/SEI 41 (2007) is the latest in a series of documents developed to assist engineers with the seismic assessment and rehabilitation of existing buildings (FEMA 273, 1997; FEMA 356, 2000). This series of documents provides a performance-based engineering framework whereby deformation and force demands for different seismic hazards are compared against deformation and force capacities for various performance levels. When the predecessor documents were developed there were limited data available on the performance of existing components, and reliability concepts were not evenly applied in the development of the criteria. The resulting criteria, especially those related to deformation capacities, tend to err on the conservative side (EERI/PEER, 2006). Anecdotal reports from practicing engineers suggest that when the criteria have been applied to older reinforced concrete buildings, most do not pass the collapse prevention limits set out in ASCE/SEI 41. Improvements to the criteria are needed to promote more accurate assessments of building vulnerability and thereby reduce unnecessary rehabilitation costs.

2.3.1 Structural performance levels and ranges

The Structural Performance Level of a building shall be selected from four discrete Structural Performance Levels and two intermediate Structural Performance Ranges defined in this section.

The discrete Structural Performance Levels are Immediate Occupancy (S-1), Life Safety (S-3), Collapse Prevention (S-5), and Not Considered (S-6). The intermediate Structural Performance Ranges are the Damage Control Range (S-2) and the Limited Safety Range (S-4). Acceptance criteria for performance within the Damage Control Structural Performance Range shall be obtained by interpolating between the acceptance criteria provided for the Immediate Occupancy and Life Safety Structural Performance Levels. Acceptance criteria for performance within the Limited Safety Structural Performance Range shall be obtained by interpolating between the acceptance criteria provided for the Life Safety and Collapse Prevention Structural Performance Levels.

<u>Immediate Occupancy Structural Performance Level (S-1):</u> Structural Performance Level S-1, Immediate Occupancy, shall be defined as the post-earthquake damage state in which a structure remains safe to occupy, essentially retains its pre-earthquake design strength and stiffness, and is in compliance with the acceptance criteria specified in this standard for this Structural Performance Level.

<u>Damage Control Structural Performance Range (S-2):</u> Structural Performance Range S-2, Damage Control, shall be defined as the continuous range of damage states between the Life Safety Structural Performance Level (S-3) and the Immediate Occupancy Structural Performance Level (S-1).

<u>Life Safety Structural Performance Level (S-3):</u> Structural Performance Level S-3, Life Safety, shall be defined as the post-earthquake damage state in which a structure has damaged components, but retains a margin against onset of partial or total collapse, and is in compliance with the acceptance criteria specified in this standard for this Structural Performance Level.

<u>Limited Safety Structural Performance Range (S-4):</u> Structural Performance Range S-4, Limited Safety, shall be defined as the continuous range of damage states between the Life Safety Structural Performance Level (S-3) and the Collapse Prevention Structural Performance Level (S-5).

Collapse Prevention Structural Performance Level (S-5): Structural Performance Level S-5, Collapse Prevention, shall be defined as the post-earthquake damage state in which a structure has damaged components and continues to support gravity loads, but retains no margin against collapse, and is in compliance with the acceptance criteria specified in this standard for this Structural Performance Level.

Structural Performance Not Considered (S-6): A building rehabilitation that does not address the performance of the structure shall be classified as Structural Performance Not Considered (S-6).

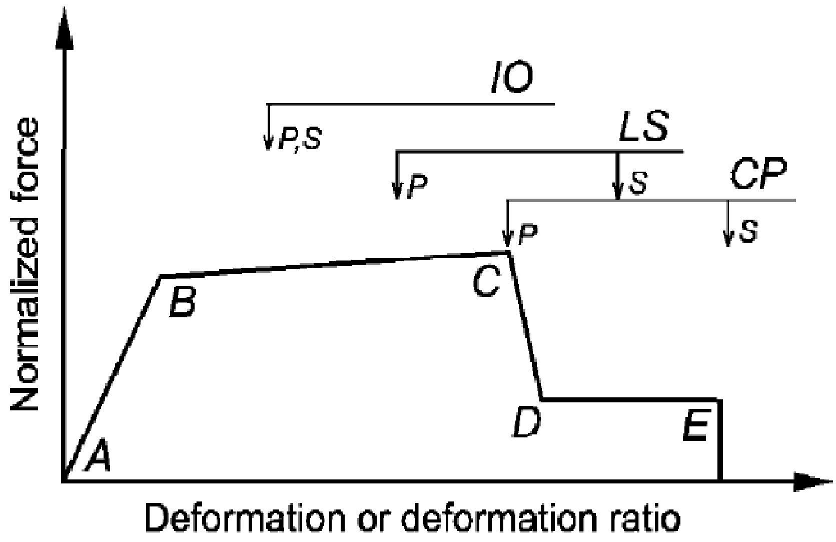

Figure 2.11 : Component or element deformation acceptance criteria (ASCE/SEI 41, 2007).

2.3.2 Determining the unit chord rotations

According to ASCE/SEI 41 2007, the failure type of component should be clarified by Table 2.3 given below;

Table 2.3: Classification of columns for determination of modelling parameters.

	Transverse Reinforcement Details		
	ACI conforming details with 135° hooks	Closed hoops with 90° hooks	Other (including lap spliced transverse reinforcement)
$V_p/(V_n/k) \leq 0.6$	Condition i	Condition ii	Condition ii
$1.0 \geq V_p/(V_n/k) \leq 0.6$	Condition ii	Condition ii	Condition iii
$V_p/(V_n/k) > 1.0$	Condition iii	Condition iii	Condition iii

To explicitly account for the flexure-shear failure mode, the proposed provisions require a column to be classified into one of three conditions based on the nominal shear strength V_n, the plastic shear demand on the column, V_p (i.e., shear demand at flexural strength of plastic hinges), and the transverse reinforcement detailing, as shown in Table 2.3. For columns with transverse reinforcement having 135° hooks, the proposed conditions correspond approximately to the following failure modes:

- Condition i: Flexure failure (flexural yielding without shear failure)
- Condition ii: Flexure-shear failure (shear failure following flexural yielding)
- Condition iii: Shear failure (shear failure before flexural yielding)

To provide further confidence of achieving a flexural failure, Condition i is limited to columns with a transverse reinforcement ratio (A_v/b_ws) greater than or equal to 0.002 and a spacing to depth ratio less than 0.5. Based on Table 2.3, for $V_p/(V_n/k)$ " 0.6, the Condition is adjusted from i to ii for columns with 90° hooks or lap-spliced transverse reinforcement to reflect the observation from experiments that poor transverse reinforcement details can result in decreased deformation capacity.

For $1.0 \geq V_p/(V_n/k) > 0.6$, the Condition is adjusted from ii to iii only for lap-spiced transverse reinforcement because the database used to evaluate the parameters for Condition ii includes columns with transverse reinforcement having 90° hooks. And also k is defined as a modifier based on ductility demand of the component. The ductility of cross section has been calculated by X-Tract analysis program.

For columns, the shear strength, V_n calculated according to Equation 2.26 shall be permitted;

$$V_n = k\frac{A_v f_y d}{s} + \lambda k\left(\frac{6\sqrt{f'c}}{M/Vd}\sqrt{1+\frac{N_u}{6\sqrt{f'_c}A_g}}\right)0.8A_g \qquad \textbf{(2.26)}$$

in which k = 1.0 in regions where displacement ductility is less than or equal to 2, 0.7 in regions where displacement ductility is greater than or equal to 6, and varies linearly for displacement ductility between 2 and 6; λ = 0.75 for lightweight aggregate concrete and 1.0 for normal weight aggregate concrete; Nu = axial compression force in pounds (= 0 for tension force); M/Vd is the largest ratio of moment to shear times effective depth under design loadings for column but shall not be taken greater than 4 or less than 2; d is the effective depth; and A_g is the gross the cross-sectional area of the column. It shall be permitted to assume d = 0.8h, where h is the dimension of the column in the direction of shear. The chord rotation capacities of reinforced concrete according to conditions given in Table 2.3, are stated in Table 2.4 based on Table 6-8 of ASCE/SEI 41 (2207)

Table 2.4: Modelling parameters and numerical acceptance criteria for nonlinear procedures- reinforced concrete columns (ASCE/SEI 41, 2007).

Conditions			Acceptance Criteria Plastic Rotations Angle, radians Performance Level				
				Component Type			
			IO	Primary		Secondary	
				LS	CP	LS	CP
Condition i							
$\frac{P}{A_g f'_c}$	$\rho = \frac{A_v}{b_w s}$						
≤ 0.1	≥ 0.006		0.005	0.026	0.035	0.045	0.060
≥ 0.6	≥ 0.006		0.003	0.008	0.009	0.009	0.010
≤ 0.1	= 0.002		0.005	0.020	0.027	0.027	0.034
≥ 0.6	= 0.002		0.002	0.003	0.004	0.004	0.005
Condition ii							
$\frac{P}{A_g f'_c}$	$\rho = \frac{A_v}{b_w s}$	$\frac{V}{b_w d \sqrt{f_c}}$					
≤ 0.1	≥ 0.006	≤ 3	0.005	0.024	0.032	0.045	0.060
≤ 0.1	≥ 0.006	≥ 6	0.005	0.019	0.025	0.045	0.060
≥ 0.6	≥ 0.006	≤ 3	0.003	0.008	0.009	0.009	0.010
≥ 0.6	≥ 0.006	≥ 6	0.003	0.006	0.007	0.007	0.008
≤ 0.1	≤ 0.0005	≤ 3	0.005	0.009	0.010	0.010	0.012
≤ 0.1	≤ 0.0005	≥ 6	0.004	0.005	0.005	0.005	0.006
≥ 0.6	≤ 0.0005	≤ 3	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
Condition iii							
$\frac{P}{A_g f'_c}$	$\rho = \frac{A_v}{b_w s}$						
≤ 0.1	≥ 0.006		0.0	0.0	0.0	0.045	0.060
≥ 0.6	≥ 0.006		0.0	0.0	0.0	0.007	0.008
≤ 0.1	= 0.002		0.0	0.0	0.0	0.005	0.006
≥ 0.6	= 0.002		0.0	0.0	0.0	0.0	0.0

The definitions of parameters in Table 2.4; P, axial load; $A_{g,}$ the gross cross-sectional area of the column; V, shear force; b_w, the width of cross section. In this thesis study, the deformation capacities of reinforced columns will be clarified according to Table 2.5 to comparison the observed damages by PEER.

3. PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER STRUCTURAL PERFORMANCE DATABASE

3.1 General

Pacific Earthquake Engineering Research Center (PEER) Structural Performance Database includes the results of uni-axial, cyclic, lateral load tests of reinforced concrete columns. The database provides the more realistic seismic performance or structural damage models. It is important for structural engineers to get more reliable assessments for the damages observed during or after earthquake in non-linear structural analysis.

This database builds on previous work at the National Institute of Standards and Technology (NIST). The original NIST database described 107 tests of rectangular reinforced columns and 92 tests of spiral-reinforced concrete columns. For each test, the NIST database provided a reference, digital top force-displacement histories, key material properties, as well as a description of the test geometry. The data was available from two reports and accompanying floppy discs (Taylor and Stone 1993; Taylor et al. 1997). With the support of the Pacific Earthquake Engineering Research Center (PEER), University of Washington researchers added new tests to the database and expanded the information available for each test. As of January 2004, the database describes 274 tests of rectangular-reinforced columns and 160 tests of spiral-reinforced columns.

The database now provides additional details of the tests, including the P-Δ configuration and the maximum column deflection imposed before reaching various damage states. (Berry et al., 2004)

The database is available on the World Wide Web from the University of Washington (http://www.ce.washington.edu/~peera1) and from PEER (http://nisee.berkeley.edu/spd/). The PEER website allows users to search for column tests with particular ranges of attributes. All detailed information of Pacific Earthquake Engineering Research Center (PEER) Structural Performance Database can be found in master thesis of Özgecan Işıltan.

3.2 Properties of Reinforced Concrete Columns in Database

The material properties, columns geometry, confinement details and test configuration of database are given with all details in master thesis of Özgecan Işıltan. However, the one of this thesis study is to clarify the volumetric ratio of transverse reinforcement of columns because the reported values of the volumetric ratios, differ from the definition for reinforced concrete columns. And so there is incoherence with these values. The volumetric ratio of columns were calculated with geometric properties of columns according to the definition of X-Tract program in order to eliminate this incompatibility and provide the conformity with analysis results taken from X-Tract Program.

3.2.1 The definition of transverse reinforcement ratio

According to manual of X-Tract program, the transverse reinforcement ratio is defined in two directions of section as x-direction and y-direction. In this definition, the transverse reinforcing ratio in one of the two principal directions as x transverse steel reinforcing ratio (ρ_x), can be calculated by taking a 'cut' across the section in the x-direction.

The ratio may be calculated as follows: ρ_x = (the total area of all transverse steel the cut passed through within a depth of one transverse reinforcement spacing) / [(the section dimension in the X direction)*(transverse reinforcement spacing)] and for the other direction as y transverse steel reinforcing ratio (ρ_y), can be calculated with the same formula

In this thesis study, the transverse reinforcement ratios of cross sections have been calculated with similar method with X-Tract program. And this method is given below;

$$\rho_x = \frac{\Sigma A_v}{(b_x.s)} \tag{3.1}$$

$$\rho_y = \frac{\Sigma A_v}{(b_y.s)} \tag{3.2}$$

In Equation 3.1 and 3.2; Av, the section area of transverse steel reinforcement; bx, the section dimension in the x-direction; by, the section dimension in the y-direction; s, the spacing distance of transverse reinforcement.

To specify the used transverse reinforcement ration in calculations of performance limits of reinforced concrete columns in thesis study, a calculation example for this ratio given below;

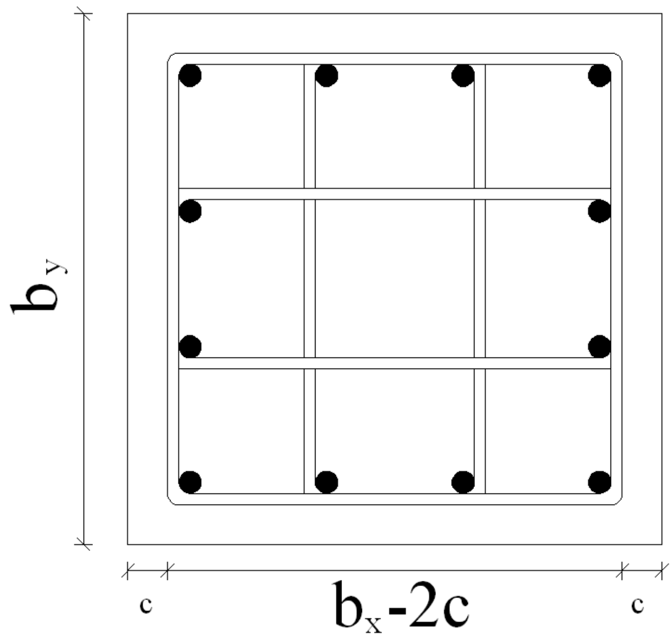

Figure 3.1 : Cross section view of reinforced concrete column.

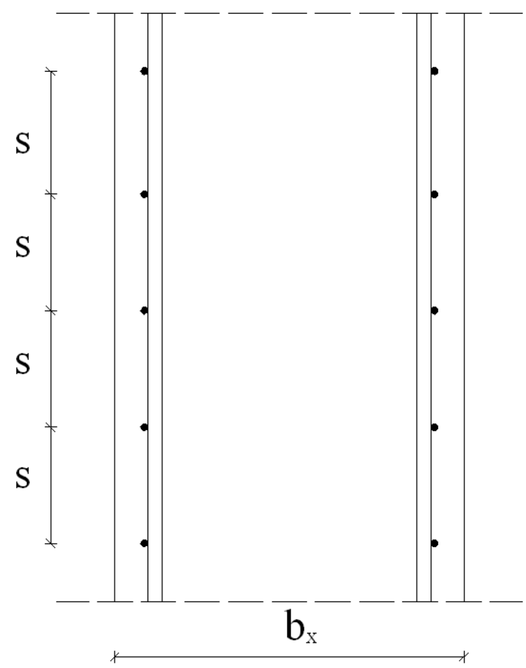

Figure 3.2 : Longitudinal section view of reinforced concrete column.

The geometric properties for L1N60 reinforced concrete column, one the specimen from PEER database, is reported from Bechtoula, Kono, Arai and Watabane in year 2002 as given below;

- The dimension of section in x-direciton: b_x = 600 mm
- The dimension of section in y-direciton: b_y = 600 mm
- The cover thickness of column: c = 44.5 mm
- The spacing distance of transverse reinforcement: s = 100 mm
- The number of shear leg is equal to 4.
- The diameter of the transverse reinforcement is equal to 12.7 mm.

According to Equation 3.1 and Equation 3.2, the transverse reinforcement ratios of L1N60 column:

- $\Sigma A_{vx-y} = 4x\left(\dfrac{3.14x12.7^2}{4}\right)$ = 506.45 mm^2
- $\rho_x = \dfrac{\Sigma A_v}{(b_x.s)} = \dfrac{506.45}{600x100}$ = 0.00844
- $\rho_y = \dfrac{\Sigma A_v}{(b_x.s)} = \dfrac{506.45}{600x100}$ = 0.00844

The transverse reinforcement ratios for two principal direction of column is determined as 0.00844. These values were used in calculations of confined concrete model in X-Tract program. And also total transverse reinforcement ratio of section is used when the crushing strain of confined concrete in X-Tract Program. This total ratio is calculated as;

- Total reinforcement ratio = $\rho_x + \rho_y$ = 0.00844 + 0.00844 = 0.01688

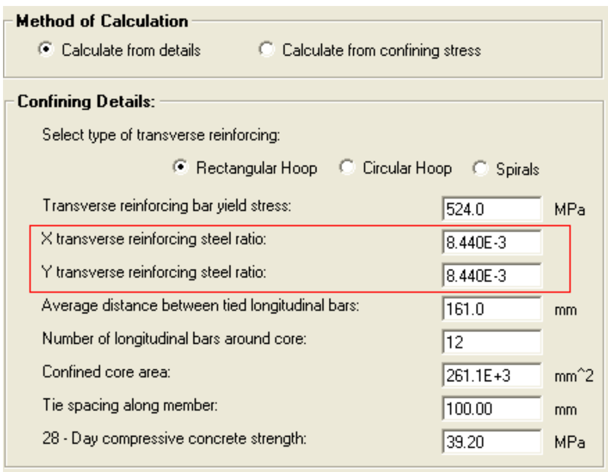

Figure 3.3 : Volumetric Definition Table for L1N60 Column in X-Tract.

3.3 Assumptions of Observed Damages

The maximum column deflections prior to observing a particular level of damage, Δ_{Damage}, (showed in Figure 3.3) are provided for column tests in which the deflection was reported in the research reports.

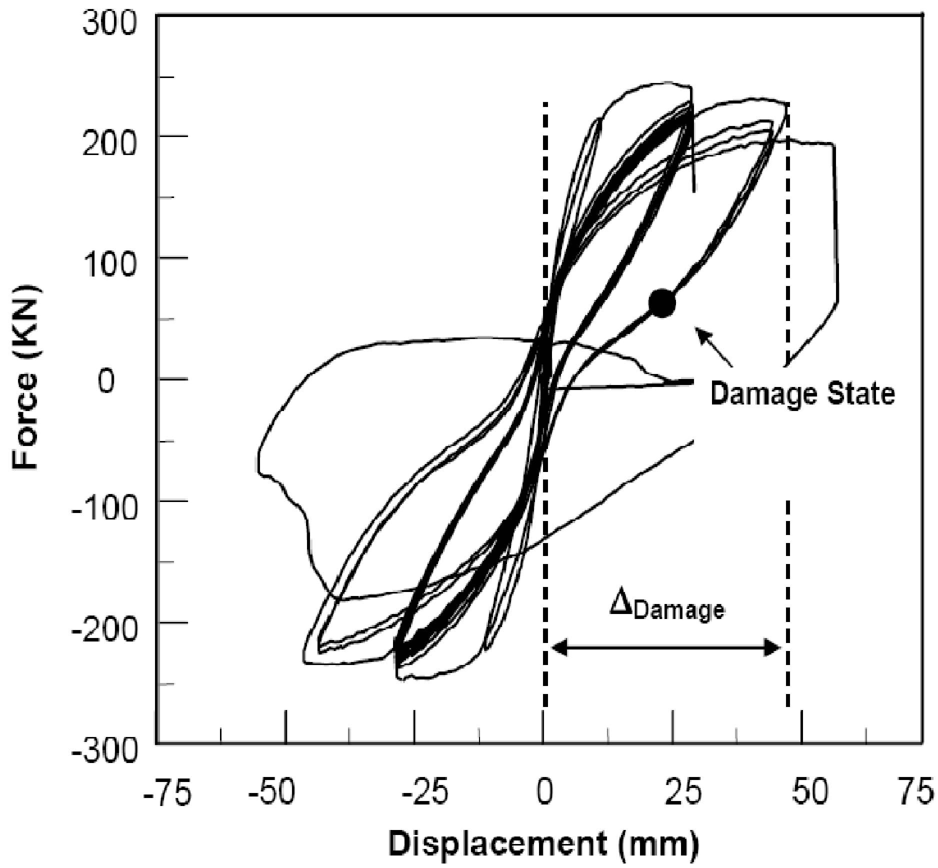

Figure 3.4 : Definition of displacement preceding damage state (Berry et al., 2004).

The damage deformations, Δ_{Damage}, are provided for the seven damage states with yielding damage defined below.

- $F_{firstyield}$ is the effective force at first yield, which was obtained by dividing the moment at first yield by the effective length. The moment at first yield was calculated with moment-curvature analysis, by assuming that the extreme tensile reinforcement had yielded or the concrete had reached a compressive strain of 0.002, whichever came first. In this moment-curvature analysis, the Mander et al. (1988) constitutive model was used to model the concrete, and the ACI (2002) steel constitutive model was used to model the response of the longitudinal reinforcement (Berry and Eberhard, 2003).

- Cover spalling, defined as the first observation of spalling. Not all damage levels were reported for each test. For these specimens, cover spalling deformation is taken as 75% of the deflection at 20% loss in flexural strength of cross section (Figure 3.4).

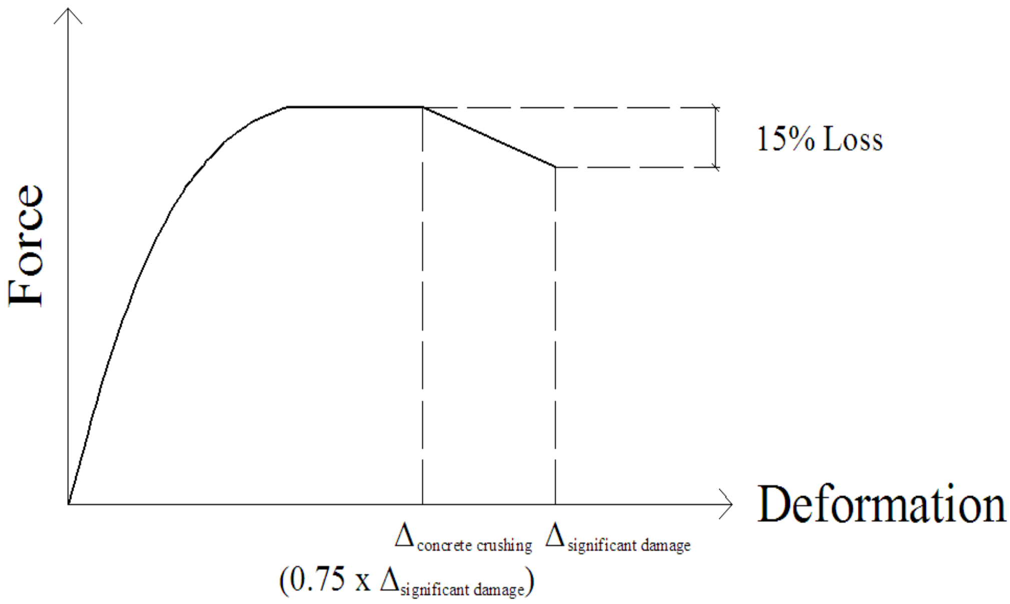

Figure 3.5 : Damage Assumption (Işıltan, 2010).

- Significant damage, defined by the reported observation of “significant spalling” or “considerable spalling.” Alternatively, if spall heights could be determined, significant spalling was defined as a spall height equal to at least 10% of the cross-section depth.

- Onset of bar buckling, defined as the observation of the first sign of longitudinal bar buckling.

- Longitudinal bar fracture, defined as the observation of the first sign of a longitudinal bar fracturing.

- Transverse reinforcement fracture, defined as the observation of the first sign of the transverse reinforcement fracturing, or becoming untied.

- Loss of axial-load capacity, defined as the observation of loss of axial-load carrying capacity of the column. Column failure (reported for 49 tests), defined for the purpose of this database, as the first occurrence of one of the following events: buckling of a longitudinal bar, fracture of transverse reinforcement, fracture of a longitudinal bar, or loss of axial-load capacity.

The relation between the observed damages of specimens and the performance limits given by codes for these reinforced concrete columns, is given below (Işıltan, 2010);

- Yielding drift is assumed as minimum damage limit.
- Concrete crushing is assumed as significant damage limit.
- Significant damage is assumed as extreme damage limit.
- Longitudinal and transverse reinforcement fracture and loss of axial-load capacity are assumed as collapsing region.

3.4 General Information for Specimens Used in Thesis Study

In PEER database, reinforced concrete columns are very variable with their geometric, material, reinforcement properties and failure types. Therefore, the boundary conditions of specimens used in this study should be accepted and given in following sections.

3.4.1 The limit conditions for circular columns

In this thesis study, 19 numbers of circular columns from PEER database, were used for comparison the test results with the performance limits given seismic codes.

The boundary conditions for these circular columns are given below;

- Failure type : Flexural Failure.
- Concrete strength: The limit value is equal to 40 MPa.
- Axial load ratio: From 0.1 and 0.6.
- Longitudinal reinforcement ratio: From 0.01 to 0.04.
- Transverse reinforcement ratio: From 0.01 to 0.03.
- Test configuration: Cantilever column.

3.4.2 Information for circular columns

The general information for circular columns are given in following table and all material, geometric, transverse reinforcement, longitudinal reinforcement properties and loading information are given in Appendix A.1.

Table 3.1: Specimen information for circular columns.

Name	Researcher	Year
No.1	Wong et al.	1990
No.3	Wong et al.	1990
Model N1	Choek and Stone	1986
Model N2	Choek and Stone	1986
Model N4	Choek and Stone	1986
Model N5	Choek and Stone	1986
Model N6	Choek and Stone	1986
A10	Kunnath et al.	1997
A11	Kunnath et al.	1997
A12	Kunnath et al.	1997
FL1	Kowalsky et al.	1996
FL2	Kowalsky et al.	1996
FL3	Kowalsky et al.	1996
Con1	Lim et al.	1990
Con2	Lim et al.	1990
Con3	Lim et al.	1990
415p	Henry	1998
Test 3	Chai, Priestley, and Seible	1991
Column 1	Coffman et al.	1993

The height of reinforced concrete columns were taken according to the upper point where the records taken from there. This height is given as L-Measured in PEER database. The force-deflection histories provided by the test researchers were modified as little as possible. Where necessary, units were converted to kN and mm, and depending on the test configuration, factors of 1/2 were introduced into the force or deflection history so that all columns could be treated as cantilevers (Berry et al., 2004). The axial load ratio can be defined as;

$$\nu = \frac{P}{f_c\left(\frac{\pi D^2}{4}\right)} \tag{3.3}$$

In Equation 3.3; P, axial load; f_c, concrete strength; b, width of cross section; h, depth of cross section.

3.4.3 The limit conditions for rectangular columns

In this thesis study, 33 numbers of rectangular columns from PEER database, were used for comparison the test results with the performance limits given seismic codes. The boundary conditions for rectangular columns are given below;

- Failure type : Flexural Failure.
- Concrete strength: The limit value is equal to 40 MPa.
- Axial load ratio: From 0.1 and 0.6.
- Longitudinal reinforcement ratio: From 0.01 to 0.04.
- Transverse reinforcement ratio: From 0.01 to 0.03.
- Test configuration: Cantilever column.

3.4.4 Information for rectangular columns

The general information for rectangular columns are given in following table and all material, geometric, transverse reinforcement, longitudinal reinforcement properties and loading information are given in Appendix A.1.

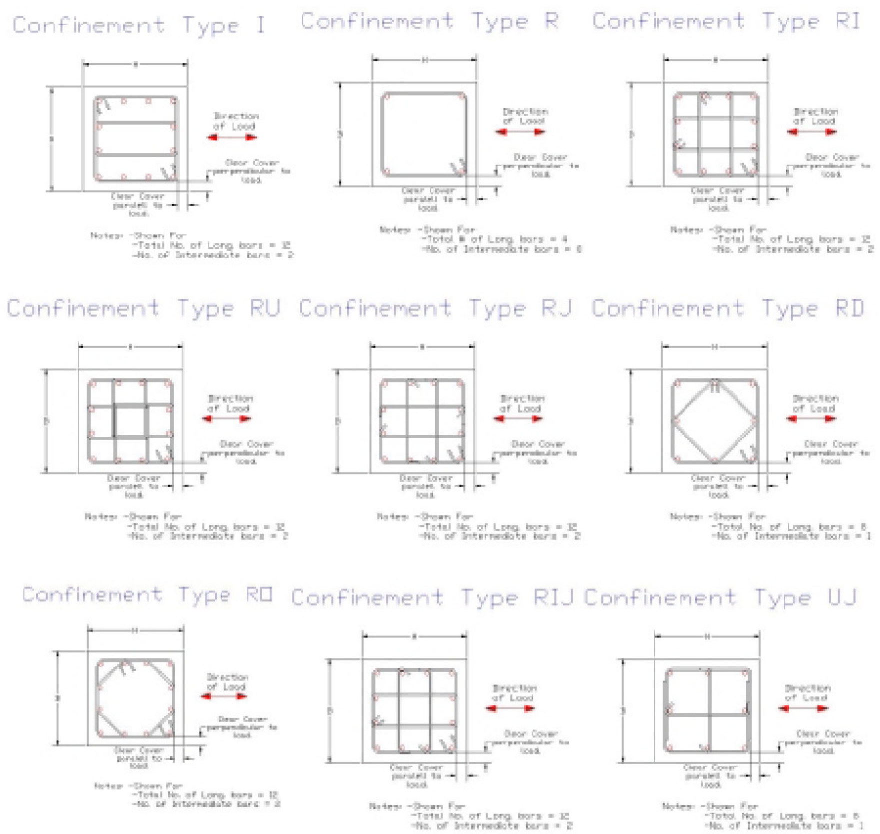

Figure 3.6 : Confinement Types.

Table 3.2: Specimen information for rectangular columns.

Name	Researcher	Year
L1N60	Bechtoula, Kono, Arai and Watanabe	2002
L1N6B	Bechtoula, Kono, Arai and Watanabe	2002
C5-40N	Matamoros et al.	1999
C5-40S	Matamoros et al.	1999
C1-1	Mo and Wang	2000
C1-2	Mo and Wang	2000
C1-3	Mo and Wang	2000
C2-1	Mo and Wang	2000
C2-2	Mo and Wang	2000
C2-3	Mo and Wang	2000
C3-1	Mo and Wang	2000
C3-2	Mo and Wang	2000
C3-3	Mo and Wang	2000
BG-1	Saatcioglu and Grira	1999
BG-2	Saatcioglu and Grira	1999
BG-3	Saatcioglu and Grira	1999
BG-4	Saatcioglu and Grira	1999
BG-5	Saatcioglu and Grira	1999
BG-6	Saatcioglu and Grira	1999
BG-7	Saatcioglu and Grira	1999
BG-8	Saatcioglu and Grira	1999
BG-9	Saatcioglu and Grira	1999
BG-10	Saatcioglu and Grira	1999
U3	Saatcioglu and Ozcebe	1989
U4	Saatcioglu and Ozcebe	1989
U6	Saatcioglu and Ozcebe	1989
U7	Saatcioglu and Ozcebe	1989
No.5	Tanaka and Park	1990
No.6	Tanaka and Park	1990
No.7	Tanaka and Park	1990
No.8	Tanaka and Park	1990
A2	Wehbe et al.	1998

The axial load ratio can be defined as;

$$\nu = \frac{P}{f_c bh} \qquad \textbf{(3.4)}$$

4. COMPARISON OF ANALYSIS RESULTS AND DAMAGE LIMITS

In this section, the damage limits will be determined according to Turkish Seismic Code, Eurocode and ASCE. And then these determined limits are converted the displacements to compare them with experimental results from PEER database.

The deformation capacities proposed by Turkish Seismic Code 2007 of specimens were calculated according to the method given in **Section 2.1.2**. Firstly, the moment-curvature diagrams (Figure 4.1) of specimens are obtained with X-Tract program. For the unconfined and confined concrete model is modeled according to Mander et al.(1988) model. After X-Tract analysis, the curvature values were determined for yielding point and values at the deformation capacities given in Turkish Seismic Code 2007. These calculated curvature values were converted the deflection directly for the yielding point and the plastic rotations for the other limit points. During getting plastic rotations, the plastic curvatures were multiplied with plastic hinge lengths as given **Eq. 2.1**. Finally, these calculated plastic displacements were added to yield displacements to get the total displacement for the deformation capacities given in seismic code.

For Eurocode, the specimens were modeled in X-Tract program. For the unconfined and confined concrete and steel reinforcement materials were modeled according to **Section 2.2.5**. After the analysis, the yield curvature and total curvature of section were determined and then the rotation capacities were gotten by using section properties and plastic hinge length. These calculated chord rotation capacities were multiplied with the clear length of specimens to get the limit displacements proposed by seismic code. Finally, the determined limit displacements were compared in following tables.

Finally, the chord rotation capacities were determined according to **Section 2.3.2**. and **Table 2.4** for all given performance levels of ASCE. After these calculated chord rotations were multiplied with the clear length of columns to get total limit displacements for all specimens.

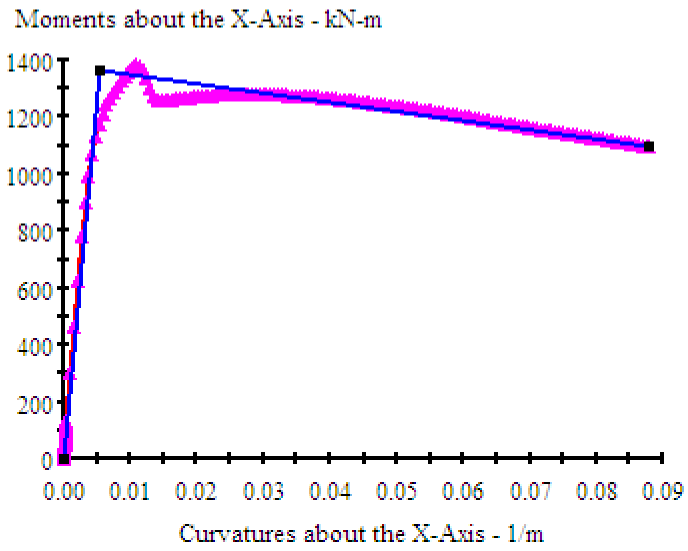

Figure 4.1 : Moment-Curvature Diagram for a Specimen.

4.1 Comparison Tables for Circular Columns

In this section, the calculated performance limits and the observed damages are compared in tables for 19 numbers of circular columns from PEER database. The performance limits are given in there levels for specimens such as minimum damage limit, significant damage limit and collapsing region. For observed damages of columns are also given for long bar buckling, long bar fracture and loss of axial load capacity. The cross-sectional area and confined concrete model of circular column as No.1 are given in Figure 4.2.

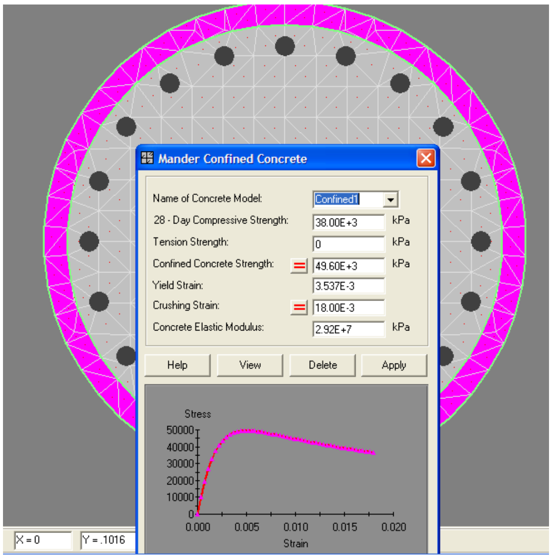

Figure 4.2 : The Cross-Sectional Area and Confined Concrete Model of No.1 from X-Tract.

4.1.1 Specimen No.1 (Wong et al.)

The observed damages reported by Wong et al. (1990) and the performance limits proposed by seismic codes are given in following **Table 4.1**, Table **4.2** and Table **4.3** for three damage limits.

Table 4.1 : Deformation capacities and observed damages for minimum damage - No.1.

Seismic Codes	**Limit Conditions**	**Minimum Damage Limits**	**Observed Damages**
			Yielding
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(MN)} = 0.0035$	4.31	5.87
	$\varepsilon_{s(MN)} = 0.0048$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0077$	5.31	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0046$	3.25	

Table 4.2 : Deformation capacities and observed damages for significant damage - No.1.

Seismic Codes	**Limit Conditions**	**Significant Damage Limits**	**Observed Damages**
			Concrete Crushing
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(GV)} = 0.0135$	17.43	6.00
	$\varepsilon_{s(GV)} = 0.0255$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0301$	20.72	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0211$	14.78	

Table 4.3 : Deformation capacities and observed damages for collapsing damage - No.1.

Seismic Codes	**Limit Conditions**	**Collapsing Damage Limits**	**Observed Damages**
			Significant Concrete Spalling
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	22.75	9.60
	$\varepsilon_{s(GÇ)} = 0.0336$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0402$	27.62	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0278$	19.50	

4.1.2 Specimen No.3 (Wong et al.)

The observed damages reported by Wong et al. (1990) and the performance limits proposed by seismic codes are given in following **Table 4.4**, **Table 4.5** and **Table 4.6** for three damage limits.

Table 4.4 : Deformation capacities and observed damages for minimum damage - No.3.

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	3.44	4.32
	$\varepsilon_{s(MN)} = 0.0027$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0081$	5.52	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0038$	2.69	

Table 4.5 : Deformation capacities and observed damages for significant damage - No.3.

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0133$	12.54	7.28
	$\varepsilon_{s(GV)} = 0.0139$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0249$	16.94	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0147$	10.30	

Table 4.6 : Deformation capacities and observed damages for collapsing damage - No.3.

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0177$	16.23	9.70
	$\varepsilon_{s(GÇ)} = 0.0182$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0333$	22.58	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0186$	13.06	

4.1.3 Specimen Model N1 (Cheok and Stone)

The observed damages reported by Cheok and Stone and the performance limits proposed by seismic codes are given in following **Table 4.7**, **Table 4.8** and **Table 4.9** for three damage limits.

Table 4.7 : Deformation capacities and observed damages for minimum damage – Model N1.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	6.44	7.39
	$\varepsilon_{s(MN)} = 0.0081$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0087$	5.91	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0049$	3.43	

Table 4.8 : Deformation capacities and observed damages for significant damage – Model N1.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0117$	-	19.30
	$\varepsilon_{s(GV)} = 0.0400$	22.74	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0539$	36.54	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0259$	17.83	

Table 4.9 : Deformation capacities and observed damages for collapsing damage – Model N1.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0175$	-	38.60
	$\varepsilon_{s(GÇ)} = 0.0600$	32.94	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0719$	48.72	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0349$	24.00	

4.1.4 Specimen Model N2 (Cheok and Stone)

The observed damages reported by Cheok and Stone and the performance limits proposed by seismic codes are given in following **Table 4.10**, **Table 4.11** and **Table 4.12** for three damage limits.

Table 4.10 : Deformation capacities and observed damages for minimum damage – Model N2.

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	5.91	6.16
	$\varepsilon_{s(MN)} = 0.0055$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0101$	6.86	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0045$	3.13	

Table 4.11 : Deformation capacities and observed damages for significant damage – Model N2.

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	20.97	22.30
	$\varepsilon_{s(GV)} = 0.0329$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0578$	39.14	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0220$	15.13	

Table 4.12 : Deformation capacities and observed damages for collapsing damage – Model N2.

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	27.39	33.50
	$\varepsilon_{s(GÇ)} = 0.0444$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0771$	52.19	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0292$	20.09	

4.1.5 Specimen Model N4 (Cheok and Stone)

The observed damages reported by Cheok and Stone and the performance limits proposed by seismic codes are given in following **Table 4.13**, **Table 4.14** and **Table 4.15** for three damage limits.

Table 4.13 : Deformation capacities and observed damages for minimum damage – Model N4.

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	6.44	4.89
	$\varepsilon_{s(MN)} = 0.0080$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0087$	5.92	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0049$	3.43	

Table 4.14 : Deformation capacities and observed damages for significant damage – Model N4.

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0115$	-	21.30
	$\varepsilon_{s(GV)} = 0.0400$	22.58	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0538$	36.47	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0260$	17.86	

Table 4.15 : Deformation capacities and observed damages for collapsing damage – Model N4.

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0175$	-	32.00
	$\varepsilon_{s(GÇ)} = 0.0600$	33.05	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0717$	48.63	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0350$	24.05	

4.1.6 Specimen Model N5 (Cheok and Stone)

The observed damages reported by Cheok and Stone and the performance limits proposed by seismic codes are given in following **Table 4.16**, **Table 4.17** and **Table 4.18** for three damage limits.

Table 4.16 : Deformation capacities and observed damages for minimum damage – Model N5.

Seismic Codes	**Limit Conditions**	**Minimum Damage Limits**	**Observed Damages**
			Yielding
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(MN)} = 0.0035$	6.01	6.31
	$\varepsilon_{s(MN)} = 0.0057$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0101$	6.88	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0045$	3.16	

Table 4.17 : Deformation capacities and observed damages for significant damage – Model N5.

Seismic Codes	**Limit Conditions**	**Significant Damage Limits**	**Observed Damages**
			Concrete Crushing
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(GV)} = 0.0135$	21.35	19.30
	$\varepsilon_{s(GV)} = 0.0337$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0569$	38.57	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0223$	15.38	

Table 4.18 : Deformation capacities and observed damages for collapsing damage – Model N5.

Seismic Codes	**Limit Conditions**	**Collapsing Damage Limits**	**Observed Damages**
			Significant Concrete Spalling
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	27.81	29.00
	$\varepsilon_{s(GÇ)} = 0.0454$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0758$	51.43	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0297$	20.47	

4.1.7 Specimen Model N6 (Cheok and Stone)

The observed damages reported by Cheok and Stone and the performance limits proposed by seismic codes are given in following **Table 4.19**, **Table 4.20** and **Table 4.21** for three damage limits.

Table 4.19 : Deformation capacities and observed damages for minimum damage – Model N6.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	20.43	14.35
	$\varepsilon_{s(MN)} = 0.0076$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0133$	18.94	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0049$	7.16	

Table 4.20 : Deformation capacities and observed damages for significant damage – Model N6.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0132$	-	33.60
	$\varepsilon_{s(GV)} = 0.0400$	56.16	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0661$	93.56	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0274$	39.49	

Table 4.21 : Deformation capacities and observed damages for collapsing damage – Model N6.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	71.85	67.20
	$\varepsilon_{s(GÇ)} = 0.0544$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0881$	124.74	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0369$	53.10	

4.1.8 Specimen A10 (Kunnath et al.)

The observed damages reported by Kunnath et al. (1997) and the performance limits proposed by seismic codes are given in following **Table 4.22**, **Table 4.23** and **Table 4.24** for three damage limits.

Table 4.22 : Deformation capacities and observed damages for minimum damage – A10.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	14.98	12.05
	$\varepsilon_{s(MN)} = 0.0068$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0112$	14.29	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0050$	6.47	

Table 4.23 : Deformation capacities and observed damages for significant damage – A10.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	47.25	32.00
	$\varepsilon_{s(GV)} = 0.0383$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0579$	73.76	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0313$	40.57	

Table 4.24 : Deformation capacities and observed damages for collapsing damage – A10.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	59.87	50.00
	$\varepsilon_{s(GÇ)} = 0.0502$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0772$	98.35	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0420$	54.52	

4.1.9 Specimen A11 (Kunnath et al.)

The observed damages reported by Kunnath et al. (1997) and the performance limits proposed by seismic codes are given in following **Table 4.25**, **Table 4.26** and **Table 4.27** for three damage limits.

Table 4.25 : Deformation capacities and observed damages for minimum damage – A11.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	14.98	12.70
	$\varepsilon_{s(MN)} = 0.0068$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0112$	14.29	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0050$	6.47	

Table 4.26 : Deformation capacities and observed damages for significant damage – A11.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	47.25	50.00
	$\varepsilon_{s(GV)} = 0.0383$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0579$	73.76	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0313$	40.57	

Table 4.27 : Deformation capacities and observed damages for collapsing damage – A11.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	59.87	105.00
	$\varepsilon_{s(GÇ)} = 0.0502$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0772$	98.35	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0420$	54.52	

4.1.10 Specimen A12 (Kunnath et al.)

The observed damages reported by Kunnath et al. (1997) and the performance limits proposed by seismic codes are given in following **Table 4.28**, **Table 4.29** and **Table 4.30** for three damage limits.

Table 4.28 : Deformation capacities and observed damages for minimum damage – A12.

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	14.98	11.24
	$\varepsilon_{s(MN)} = 0.0068$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0112$	14.29	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0050$	6.47	

Table 4.29 : Deformation capacities and observed damages for significant damage – A12.

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	47.25	50.00
	$\varepsilon_{s(GV)} = 0.0383$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0579$	73.76	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0313$	40.57	

Table 4.30 : Deformation capacities and observed damages for collapsing damage – A12.

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	59.87	81.00
	$\varepsilon_{s(GÇ)} = 0.0502$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0772$	98.35	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0420$	54.52	

4.1.11 Specimen FL1 (Kowalsky et al.)

The observed damages reported by Kowalsky et al. (1996) and the performance limits proposed by seismic codes are given in following **Table 4.31**, **Table 4.32** and **Table 4.33** for three damage limits.

Table 4.31 : Deformation capacities and observed damages for minimum damage – FL1.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	59.79	60.02
	$\varepsilon_{s(MN)} = 0.0033$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0183$	63.99	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0046$	16.11	

Table 4.32 : Deformation capacities and observed damages for significant damage – FL1.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0112$	102.01	62.25
	$\varepsilon_{s(GV)} = 0.0142$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0412$	143.42	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0236$	83.90	

Table 4.33 : Deformation capacities and observed damages for collapsing damage – FL1.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0148$	119.26	83.00
	$\varepsilon_{s(GÇ)} = 0.0185$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0549$	191.23	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0305$	108.28	

4.1.12 Specimen FL2 (Kowalsky et al.)

The observed damages reported by Kowalsky et al. (1996) and the performance limits proposed by seismic codes are given in following **Table 4.34**, **Table 4.35** and **Table 4.36** for three damage limits.

Table 4.34 : Deformation capacities and observed damages for minimum damage – FL2.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	60.01	60.24
	$\varepsilon_{s(MN)} = 0.0036$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0181$	63.36	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0044$	15.38	

Table 4.35 : Deformation capacities and observed damages for significant damage – FL2.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0082$	87.51	70.00
	$\varepsilon_{s(GV)} = 0.0010$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0323$	112.81	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0203$	72.02	

Table 4.36 : Deformation capacities and observed damages for collapsing damage – FL2.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0105$	99.21	70.00
	$\varepsilon_{s(GÇ)} = 0.0139$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0431$	150.41	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0267$	94.60	

4.1.13 Specimen FL3 (Kowalsky et al.)

The observed damages reported by Kowalsky et al. (1996) and the performance limits proposed by seismic codes are given in following **Table 4.37**, **Table 4.38** and **Table 4.39** for three damage limits.

Table 4.37 : Deformation capacities and observed damages for minimum damage – FL3.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$ $\varepsilon_{s(MN)} = 0.0034$	60.68 -	60.92
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0185$	64.61	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0045$	16.23	

Table 4.38 : Deformation capacities and observed damages for significant damage – FL3.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0108$ $\varepsilon_{s(GV)} = 0.0142$	101.75 -	68.00
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0403$	140.41	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0242$	85.96	

Table 4.39 : Deformation capacities and observed damages for collapsing damage – FL3.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0142$ $\varepsilon_{s(GÇ)} = 0.0185$	118.82 -	102.00
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0537$	187.21	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0314$	111.40	

4.1.14 Specimen Con1 (Lim et al.)

The observed damages reported by Lim et al. (1990) and the performance limits proposed by seismic codes are given in following **Table 4.40**, **Table 4.41** and **Table 4.42** for three damage limits.

Table 4.40 : Deformation capacities and observed damages for minimum damage – Con1.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	19.31	30.54
	$\varepsilon_{s(MN)} = 0.0032$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0219$	23.15	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0044$	4.89	

Table 4.41 : Deformation capacities and observed damages for significant damage – Con1.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	36.90	60.00
	$\varepsilon_{s(GV)} = 0.0162$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.1031$	108.59	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0209$	23.05	

Table 4.42 : Deformation capacities and observed damages for collapsing damage – Con1.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	43.61	75.00
	$\varepsilon_{s(GÇ)} = 0.0206$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.1375$	144.79	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0276$	30.47	

4.1.15 Specimen Con2 (Lim et al.)

The observed damages reported by Lim et al. (1990) and the performance limits proposed by seismic codes are given in following **Table 4.43**, **Table 4.43** and **Table 4.45** for three damage limits.

Table 4.43 : Deformation capacities and observed damages for minimum damage – Con2.

Seismic Codes	**Limit Conditions**	**Minimum Damage Limits**	**Observed Damages**
			Yielding
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(MN)} = 0.0035$	5.06	11.02
	$\varepsilon_{s(MN)} = 0.0032$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0152$	7.50	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0044$	2.36	

Table 4.44 : Deformation capacities and observed damages for significant damage – Con2.

Seismic Codes	**Limit Conditions**	**Significant Damage Limits**	**Observed Damages**
			Concrete Crushing
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(GV)} = 0.0135$	13.55	30.00
	$\varepsilon_{s(GV)} = 0.0162$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0846$	41.66	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0209$	11.13	

Table 4.45 : Deformation capacities and observed damages for collapsing damage – Con2.

Seismic Codes	**Limit Conditions**	**Collapsing Damage Limits**	**Observed Damages**
			Significant Concrete Spalling
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	16.79	40.00
	$\varepsilon_{s(GÇ)} = 0.0206$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.1129$	55.55	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0276$	14.71	

4.1.16 Specimen Con3 (Lim et al.)

The observed damages reported by Lim et al. (1990) and the performance limits proposed by seismic codes are given in following **Table 4.46**, **Table 4.47** and **Table 4.48** for three damage limits.

Table 4.46 : Deformation capacities and observed damages for minimum damage – Con3.

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	4.66	10.43
	$\varepsilon_{s(MN)} = 0.0026$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0153$	7.55	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0039$	2.13	

Table 4.47 : Deformation capacities and observed damages for significant damage – Con3.

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	12.58	28.00
	$\varepsilon_{s(GV)} = 0.0140$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0718$	35.36	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0169$	9.02	

Table 4.48 : Deformation capacities and observed damages for collapsing damage – Con3.

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	15.76	37.00
	$\varepsilon_{s(GÇ)} = 0.0183$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0958$	47.15	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0219$	11.66	

4.1.17 Specimen 415p (Henry)

The observed damages reported by Henry (1998) and the performance limits proposed by seismic codes are given in following **Table 4.49**, **Table 4.50** and **Table 4.51** for three damage limits.

Table 4.49 : Deformation capacities and observed damages for minimum damage – 415p.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	24.85	25.78
	$\varepsilon_{s(MN)} = 0.0077$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0098$	22.27	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0049$	11.27	

Table 4.50 : Deformation capacities and observed damages for significant damage – 415p.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0124$	-	125.00
	$\varepsilon_{s(GV)} = 0.0400$	79.33	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0467$	106.11	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0269$	61.68	

Table 4.51 : Deformation capacities and observed damages for collapsing damage – 415p.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	108.81	180.00
	$\varepsilon_{s(GÇ)} = 0.0572$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0623$	141.49	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0362$	82.77	

4.1.18 Specimen Test 3 (Chai, Priestley, and Seible)

The observed damages reported by Chai, Priestley, and Seible (1991) and the performance limits proposed by seismic codes are given in following **Table 4.52**, **Table 4.53** and **Table 4.54** for three damage limits.

Table 4.52 : Deformation capacities and observed damages for minimum damage – Test 3.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	40.87	29.11
	$\varepsilon_{s(MN)} = 0.0056$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0105$	36.75	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0044$	15.61	

Table 4.53 : Deformation capacities and observed damages for significant damage – Test 3.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0059$	58.08	110.00
	$\varepsilon_{s(GV)} = 0.0115$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0129$	45.09	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0080$	28.22	

Table 4.54 : Deformation capacities and observed damages for collapsing damage – Test 3.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0073$	66.40	140.00
	$\varepsilon_{s(GÇ)} = 0.0143$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0172$	60.12	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0128$	44.97	

4.1.19 Specimen Column 1 (Coffman et al.)

The observed damages reported by Coffman et al. (1993) and the performance limits proposed by seismic codes are given in following **Table 4.52**, **Table 4.53** and **Table 4.54** for three damage limits.

Table 4.55 : Deformation capacities and observed damages for minimum damage – Column 1.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	37.80	17.40
	$\varepsilon_{s(MN)} = 0.0049$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0137$	37.04	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0044$	12.33	

Table 4.56 : Deformation capacities and observed damages for significant damage – Column 1.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0066$	55.84	55.00
	$\varepsilon_{s(GV)} = 0.0109$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0166$	44.79	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0124$	34.18	

Table 4.57 : Deformation capacities and observed damages for collapsing damage – Column 1.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0084$	63.57	110.00
	$\varepsilon_{s(GÇ)} = 0.0134$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0222$	59.71	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0153$	42.07	

4.2 Comparison Tables for Rectangular Columns

In this section, the calculated performance limits and the observed damages are compared in tables for 33 numbers of rectangular columns from PEER database. The performance limits are given in there levels for specimens such as minimum damage limit, significant damage limit and collapsing region.

For observed damages of columns are also given for long bar buckling, long bar fracture and loss of axial load capacity. The confined concrete and steel reinforcement model of rectangular column as L1N60 are given in Figure 4.3 and Figure 4.4.

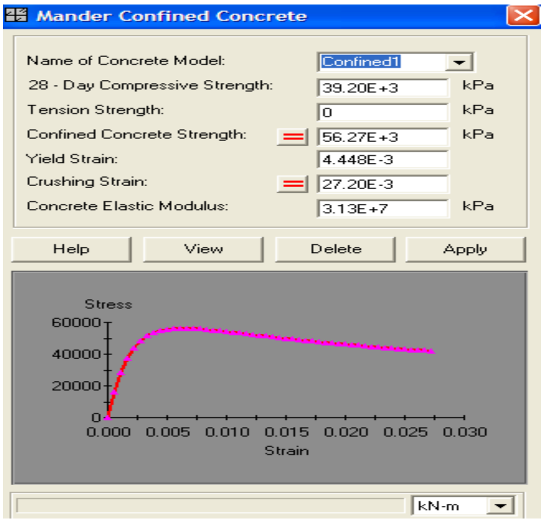

Figure 4.3 : The Confined Concrete and Steel Reinforcement Model of L1N60 from X-Tract.

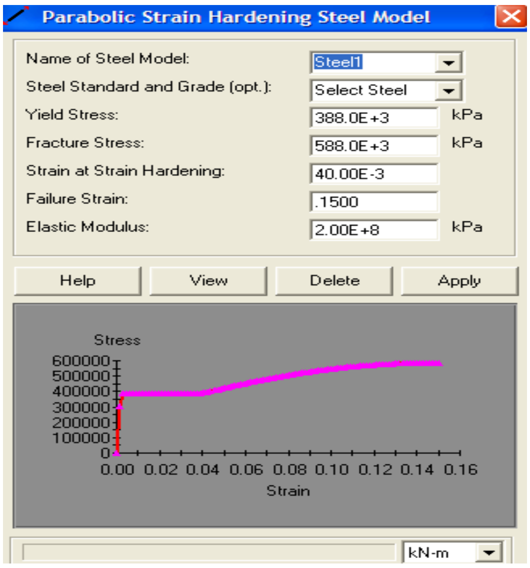

Figure 4.4 : The Confined Concrete and Steel Reinforcement Model of L1N60 from X-Tract.

4.2.1 Specimen L1N60 (Kono et al.)

The observed damages reported by Kono et al. (2002) and the performance limits proposed by seismic codes are given in following **Table 4.58**, **Table 4.59** and **Table 4.60** for three damage limits.

Table 4.58 : Deformation capacities and observed damages for minimum damage – L1N60.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages – Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	3.79	3.80
	$\varepsilon_{s(MN)} = 0.0012$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0054$	5.58	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0037$	3.89	

Table 4.59 : Deformation capacities and observed damages for significant damage – L1N60.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages – Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0134$	15.35	18.00
	$\varepsilon_{s(GV)} = 0.0081$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0184$	19.03	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0122$	12.89	

Table 4.60 : Deformation capacities and observed damages for collapsing damage – L1N60.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages – Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0179$	19.83	24.00
	$\varepsilon_{s(GÇ)} = 0.0104$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0245$	25.37	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0138$	14.58	

4.2.2 Specimen L1N6B (Kono et al.)

The observed damages reported by Kono et al. (2002) and the performance limits proposed by seismic codes are given in following **Table 4.61**, **Table 4.62** and **Table 4.63** for three damage limits.

Table 4.61 : Deformation capacities and observed damages for minimum damage – L1N6B.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	4.17	3.69
	$\varepsilon_{s(MN)} = 0.0014$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0063$	6.49	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0037$	4.00	

Table 4.62 : Deformation capacities and observed damages for significant damage – L1N6B.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	16.01	25.50
	$\varepsilon_{s(GV)} = 0.0101$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0196$	20.17	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0112$	11.96	

Table 4.63 : Deformation capacities and observed damages for collapsing damage – L1N6B.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	20.86	34.00
	$\varepsilon_{s(GÇ)} = 0.0133$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0261$	26.90	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0131$	13.92	

4.2.3 Specimen C5-40N (Matamoros)

The observed damages reported by Matamoros (1999) and the performance limits proposed by seismic codes are given in following **Table 4.64**, **Table 4.65** and **Table 4.66** for three damage limits.

Table 4.64 : Deformation capacities and observed damages for minimum damage – (C5-40N).

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	3.79	8.24
	$\varepsilon_{s(MN)} = 0.0024$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0107$	6.56	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0043$	2.44	

Table 4.65 : Deformation capacities and observed damages for significant damage – (C5-40N).

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0099$	8.70	14.00
	$\varepsilon_{s(GV)} = 0.0065$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0241$	12.03	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0224$	12.57	

Table 4.66 : Deformation capacities and observed damages for collapsing damage – (C5-40N).

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0130$	10.19	18.70
	$\varepsilon_{s(GÇ)} = 0.0068$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0321$	16.04	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0264$	14.78	

4.2.4 Specimen C5-40S (Matamoros)

The observed damages reported by Matamoros (1999) and the performance limits proposed by seismic codes are given in following **Table 4.67**, **Table 4.68** and **Table 4.69** for three damage limits.

Table 4.67 : Deformation capacities and observed damages for minimum damage – (C5-40S).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	3.78	8.10
	$\varepsilon_{s(MN)} = 0.0024$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0106$	6.52	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0043$	2.43	

Table 4.68 : Deformation capacities and observed damages for significant damage – (C5-40S).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0091$	8.14	14.00
	$\varepsilon_{s(GV)} = 0.0060$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0208$	10.41	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0222$	12.46	

Table 4.69 : Deformation capacities and observed damages for collapsing damage – (C5-40S).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0119$	9.79	18.60
	$\varepsilon_{s(GÇ)} = 0.0071$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0278$	13.88	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0262$	14.67	

4.2.5 Specimen C1-1 (Mo and Wang)

The observed damages reported by Mo and Wang (2000) and the performance limits proposed by seismic codes are given in following **Table 4.70**, **Table 4.71** and **Table 4.72** for three damage limits.

Table 4.70 : Deformation capacities and observed damages for minimum damage – (C1-1).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	13.94	14.95
	$\varepsilon_{s(MN)} = 0.0037$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0109$	13.47	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0049$	6.43	

Table 4.71 : Deformation capacities and observed damages for significant damage – (C1-1).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	45.22	42.50
	$\varepsilon_{s(GV)} = 0.0172$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0463$	57.09	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0260$	33.84	

Table 4.72 : Deformation capacities and observed damages for collapsing damage – (C1-1).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	57.26	69.50
	$\varepsilon_{s(GÇ)} = 0.0220$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0617$	76.11	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0349$	45.49	

4.2.6 Specimen C1-2 (Mo and Wang)

The observed damages reported by Mo and Wang (2000) and the performance limits proposed by seismic codes are given in following **Table 4.73**, **Table 4.74** and **Table 4.75** for three damage limits.

Table 4.73 : Deformation capacities and observed damages for minimum damage – (C1-2).

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	13.29	14.79
	$\varepsilon_{s(MN)} = 0.0066$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0113$	14.01	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0047$	6.21	

Table 4.74 : Deformation capacities and observed damages for significant damage – (C1-2).

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	42.35	37.00
	$\varepsilon_{s(GV)} = 0.0300$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0398$	49.27	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0243$	31.71	

Table 4.75 : Deformation capacities and observed damages for collapsing damage – (C1-2).

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	53.11	63.00
	$\varepsilon_{s(GÇ)} = 0.0382$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0531$	65.69	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0326$	42.39	

4.2.7 Specimen C1-3 (Mo and Wang)

The observed damages reported by Mo and Wang (2000) and the performance limits proposed by seismic codes are given in following **Table 4.76**, **Table 4.77** and **Table 4.78** for three damage limits.

Table 4.76 : Deformation capacities and observed damages for minimum damage – (C1-3).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	12.18	14.87
	$\varepsilon_{s(MN)} = 0.0053$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0118$	14.60	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0046$	5.93	

Table 4.77 : Deformation capacities and observed damages for significant damage – (C1-3).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0103$	31.09	36.00
	$\varepsilon_{s(GV)} = 0.0200$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0387$	47.81	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0223$	29.03	

Table 4.78 : Deformation capacities and observed damages for collapsing damage – (C1-3).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0135$	38.82	62.00
	$\varepsilon_{s(GÇ)} = 0.0259$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0516$	63.75	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0296$	38.49	

4.2.8 Specimen C2-1 (Mo and Wang)

The observed damages reported by Mo and Wang (2000) and the performance limits proposed by seismic codes are given in following **Table 4.79**, **Table 4.80** and **Table 4.81** for three damage limits.

Table 4.79 : Deformation capacities and observed damages for minimum damage – (C2-1).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	13.97	16.71
	$\varepsilon_{s(MN)} = 0.0075$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0111$	13.70	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0049$	6.44	

Table 4.80 : Deformation capacities and observed damages for significant damage – (C2-1).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	45.22	37.00
	$\varepsilon_{s(GV)} = 0.0332$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0447$	55.16	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0256$	33.28	

Table 4.81 : Deformation capacities and observed damages for collapsing damage – (C2-1).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	57.26	63.00
	$\varepsilon_{s(GÇ)} = 0.0433$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0596$	73.54	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0344$	44.75	

4.2.9 Specimen C2-2 (Mo and Wang)

The observed damages reported by Mo and Wang (2000) and the performance limits proposed by seismic codes are given in following **Table 4.82**, **Table 4.83** and **Table 4.84** for three damage limits.

Table 4.82 : Deformation capacities and observed damages for minimum damage – (C2-2).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages – Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	13.28	15.62
	$\varepsilon_{s(MN)} = 0.0067$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0112$	13.95	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0047$	6.21	

Table 4.83 : Deformation capacities and observed damages for significant damage – (C2-2).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages – Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0130$	40.75	35.00
	$\varepsilon_{s(GV)} = 0.0288$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0384$	47.09	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0240$	31.20	

Table 4.84 : Deformation capacities and observed damages for collapsing damage – (C2-2).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages – Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0173$	51.17	68.00
	$\varepsilon_{s(GÇ)} = 0.0368$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0512$	63.32	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0321$	41.74	

4.2.10 Specimen C2-3 (Mo and Wang)

The observed damages reported by Mo and Wang (2000) and the performance limits proposed by seismic codes are given in following **Table 4.85**, **Table 4.86** and **Table 4.87** for three damage limits.

Table 4.85 : Deformation capacities and observed damages for minimum damage – (C2-3).

Seismic Codes	**Limit Conditions**	**Minimum Damage Limits**	**Observed Damages**
			Yielding
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(MN)} = 0.0035$	12.30	13.45
	$\varepsilon_{s(MN)} = 0.0054$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0117$	14.55	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0046$	5.93	

Table 4.86 : Deformation capacities and observed damages for significant damage – (C2-3).

Seismic Codes	**Limit Conditions**	**Significant Damage Limits**	**Observed Damages**
			Concrete Crushing
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(GV)} = 0.0099$	30.20	38.00
	$\varepsilon_{s(GV)} = 0.0193$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0370$	45.77	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0220$	28.65	

Table 4.87 : Deformation capacities and observed damages for collapsing damage – (C2-3).

Seismic Codes	**Limit Conditions**	**Collapsing Damage Limits**	**Observed Damages**
			Significant Concrete Spalling
		(mm)	**(mm)**
TSC	$\varepsilon_{cu(GÇ)} = 0.0130$	37.84	58.00
	$\varepsilon_{s(GÇ)} = 0.0252$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0493$	61.03	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0292$	38.06	

4.2.11 Specimen C3-1 (Mo and Wang)

The observed damages reported by Mo and Wang (2000) and the performance limits proposed by seismic codes are given in following **Table 4.88**, **Table 4.89** and **Table 4.90** for three damage limits.

Table 4.88 : Deformation capacities and observed damages for minimum damage – (C3-1).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages – Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	14.22	17.91
	$\varepsilon_{s(MN)} = 0.0080$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0115$	14.27	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0049$	6.47	

Table 4.89 : Deformation capacities and observed damages for significant damage – (C3-1).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages – Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0129$	43.45	48.80
	$\varepsilon_{s(GV)} = 0.0326$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0380$	47.02	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0257$	33.49	

Table 4.90 : Deformation capacities and observed damages for collapsing damage – (C3-1).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages – Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0171$	55.59	65.00
	$\varepsilon_{s(GÇ)} = 0.0423$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0507$	62.69	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0346$	45.05	

4.2.12 Specimen C3-2 (Mo and Wang)

The observed damages reported by Mo and Wang (2000) and the performance limits proposed by seismic codes are given in following **Table 4.91**, **Table 4.92** and **Table 4.93** for three damage limits.

Table 4.91 : Deformation capacities and observed damages for minimum damage – (C3-2).

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	13.43	17.89
	$\varepsilon_{s(MN)} = 0.0068$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0115$	14.29	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0048$	6.22	

Table 4.92 : Deformation capacities and observed damages for significant damage – (C3-2).

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0125$	39.76	52.50
	$\varepsilon_{s(GV)} = 0.0280$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0371$	45.97	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0240$	31.29	

Table 4.93 : Deformation capacities and observed damages for collapsing damage – (C3-2).

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0166$	49.56	70.00
	$\varepsilon_{s(GÇ)} = 0.0355$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0495$	61.29	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0322$	41.88	

4.2.13 Specimen C3-3 (Mo and Wang)

The observed damages reported by Mo and Wang (2000) and the performance limits proposed by seismic codes are given in following **Table 4.94**, **Table 4.95** and **Table 4.96** for three damage limits.

Table 4.94 : Deformation capacities and observed damages for minimum damage – (C3-3).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	12.45	15.43
	$\varepsilon_{s(MN)} = 0.0055$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0120$	14.92	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0045$	5.93	

Table 4.95 : Deformation capacities and observed damages for significant damage – (C3-3).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0096$	29.23	51.00
	$\varepsilon_{s(GV)} = 0.0185$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0360$	44.53	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.220$	28.69	

Table 4.96 : Deformation capacities and observed damages for collapsing damage – (C3-3).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0126$	36.65	68.00
	$\varepsilon_{s(GÇ)} = 0.0243$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0480$	59.37	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0293$	38.12	

4.2.14 Specimen BG-1 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.97**, **Table 4.98** and **Table 4.99** for three damage limits.

Table 4.97 : Deformation capacities and observed damages for minimum damage – (BG-1).

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	12.47	
	$\varepsilon_{s(MN)} = 0.0021$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0099$	14.99	9.99
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0034$	5.23	

Table 4.98 : Deformation capacities and observed damages for significant damage – (BG-1).

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0078$	20.86	
	$\varepsilon_{s(GV)} = 0.0054$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0152$	22.84	26.30
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0115$	17.95	

Table 4.99 : Deformation capacities and observed damages for collapsing damage – (BG-1).

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0100$	24.60	
	$\varepsilon_{s(GÇ)} = 0.0068$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0202$	30.45	35.00
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0149$	23.26	

4.2.15 Specimen BG-2 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.100**, **Table 4.101** and Table **4.102** for three damage limits.

Table 4.100 : Deformation capacities and observed damages for minimum damage - (BG-2).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	12.63	9.64
	$\varepsilon_{s(MN)} = 0.0022$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0095$	14.38	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0040$	6.26	

Table 4.101 : Deformation capacities and observed damages for significant damage – (BG-2).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0120$	30.58	39.80
	$\varepsilon_{s(GV)} = 0.0106$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0277$	41.62	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0169$	26.36	

Table 4.102 : Deformation capacities and observed damages for collapsing damage – (BG-2).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0160$	37.98	53.00
	$\varepsilon_{s(GÇ)} = 0.0138$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0369$	55.50	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0210$	32.75	

4.2.16 Specimen BG-3 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.103**, **Table 4.104** and **Table 4.105** for three damage limits.

Table 4.103 : Deformation capacities and observed damages for minimum damage – (BG-3).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	18.12	15.40
	$\varepsilon_{s(MN)} = 0.0059$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0118$	17.83	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0047$	7.33	

Table 4.104 : Deformation capacities and observed damages for significant damage – (BG-3).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	53.63	82.50
	$\varepsilon_{s(GV)} = 0.0295$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0446$	67.00	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0253$	39.52	

Table 4.105 : Deformation capacities and observed damages for collapsing damage – (BG-3).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	64.03	110.00
	$\varepsilon_{s(GÇ)} = 0.0353$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0595$	89.33	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0336$	52.33	

4.2.17 Specimen BG-4 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.106**, **Table 4.107** and **Table 4.108** for three damage limits.

Table 4.106 : Deformation capacities and observed damages for minimum damage – (BG-4).

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	12.69	11.01
	$\varepsilon_{s(MN)} = 0.0010$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0097$	14.70	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0034$	5.35	

Table 4.107 : Deformation capacities and observed damages for significant damage – (BG-4).

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0092$	23.18	35.30
	$\varepsilon_{s(GV)} = 0.0020$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0171$	25.81	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0121$	18.90	

Table 4.108 : Deformation capacities and observed damages for collapsing damage – (BG-4).

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0120$	27.42	47.00
	$\varepsilon_{s(GÇ)} = 0.0030$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0229$	34.41	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0152$	23.77	

4.2.18 Specimen BG-5 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.109**, **Table 4.110** and **Table 4.111** for three damage limits.

Table 4.109 : Deformation capacities and observed damages for minimum damage – (BG-5).

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	13.29	
	$\varepsilon_{s(MN)} = 0.0021$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0104$	15.74	13.76
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0026$	4.13	

Table 4.110 : Deformation capacities and observed damages for significant damage – (BG-5).

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	34.40	
	$\varepsilon_{s(GV)} = 0.0121$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0360$	54.11	65.30
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0064$	9.94	

Table 4.111 : Deformation capacities and observed damages for collapsing damage – (BG-5).

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	42.92	
	$\varepsilon_{s(GÇ)} = 0.0159$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0480$	72.15	87.00
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0089$	13.87	

4.2.19 Specimen BG-6 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.112**, **Table 4.113** and **Table 4.114** for three damage limits.

Table 4.112 : Deformation capacities and observed damages for minimum damage – (BG-6).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	13.20	11.31
	$\varepsilon_{s(MN)} = 0.0019$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0116$	17.04	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0026$	4.18	

Table 4.113 : Deformation capacities and observed damages for significant damage – (BG-6).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	29.72	61.50
	$\varepsilon_{s(GV)} = 0.0072$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0322$	47.07	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0065$	10.23	

Table 4.114 : Deformation capacities and observed damages for collapsing damage – (BG-6).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	35.61	82.00
	$\varepsilon_{s(GÇ)} = 0.0083$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0433$	62.76	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0091$	14.25	

4.2.20 Specimen BG-7 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.115**, **Table 4.116** and **Table 4.117** for three damage limits.

Table 4.115 : Deformation capacities and observed damages for minimum damage – (BG-7).

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$ $\varepsilon_{s(MN)} = 0.0010$	12.87 -	11.97
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0100$	15.02	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0033$	5.20	

Table 4.116 : Deformation capacities and observed damages for significant damage – (BG-7).

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0091$ $\varepsilon_{s(GV)} = 0.0020$	23.51 -	63.00
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0204$	30.60	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0118$	18.45	

Table 4.117 : Deformation capacities and observed damages for collapsing damage – (BG-7).

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0118$ $\varepsilon_{s(GÇ)} = 0.0030$	27.93 -	84.00
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0272$	40.80	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0149$	23.27	

4.2.21 Specimen BG-8 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.118**, **Table 4.119** and **Table 4.120** for three damage limits.

Table 4.118 : Deformation capacities and observed damages for minimum damage – (BG-8).

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	17.17	20.66
	$\varepsilon_{s(MN)} = 0.0048$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0124$	18.70	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0044$	6.89	

Table 4.119 : Deformation capacities and observed damages for significant damage – (BG-8).

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0091$	34.50	72.00
	$\varepsilon_{s(GV)} = 0.0158$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0322$	48.35	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0200$	31.25	

Table 4.120 : Deformation capacities and observed damages for collapsing damage – (BG-8).

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0118$	42.32	96.00
	$\varepsilon_{s(GÇ)} = 0.0205$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0430$	64.46	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0266$	41.51	

4.2.22 Specimen BG-9 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.121**, **Table 4.122** and **Table 4.123** for three damage limits.

Table 4.121 : Deformation capacities and observed damages for minimum damage – (BG-9).

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	12.90	12.41
	$\varepsilon_{s(MN)} = 0.0028$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0096$	14.63	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0034$	5.29	

Table 4.122 : Deformation capacities and observed damages for significant damage – (BG-9).

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0091$	23.93	55.50
	$\varepsilon_{s(GV)} = 0.0087$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0194$	29.59	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0118$	18.45	

Table 4.123 : Deformation capacities and observed damages for collapsing damage – (BG-9).

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0118$	28.71	74.00
	$\varepsilon_{s(GÇ)} = 0.0114$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0259$	39.45	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0149$	23.27	

4.2.23 Specimen BG-10 (Saatcioglu and Grira)

The observed damages reported by Saatcioglu and Grira (1999) and the performance limits proposed by seismic codes are given in following **Table 4.124**, **Table 4.125** and **Table 4.126** for three damage limits.

Table 4.124 : Deformation capacities and observed damages for minimum damage – (BG-10).

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	13.33	13.62
	$\varepsilon_{s(MN)} = 0.0021$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0102$	15.53	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0044$	6.86	

Table 4.125 : Deformation capacities and observed damages for significant damage – (BG-10).

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	34.99	66.80
	$\varepsilon_{s(GV)} = 0.0127$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0344$	52.25	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0192$	29.91	

Table 4.126 : Deformation capacities and observed damages for collapsing damage – (BG-10).

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	44.26	89.00
	$\varepsilon_{s(GÇ)} = 0.0173$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0458$	69.67	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0230$	35.93	

4.2.24 Specimen U3 (Saatcioglu and Ozcebe)

The observed damages reported by Saatcioglu and Ozcebe (1989) and the performance limits proposed by seismic codes are given in following **Table 4.127**, **Table 4.128** and **Table 4.129** for three damage limits.

Table 4.127 : Deformation capacities and observed damages for minimum damage – U3.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	8.19	20.80
	$\varepsilon_{s(MN)} = 0.0066$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0103$	8.78	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0048$	4.41	

Table 4.128 : Deformation capacities and observed damages for significant damage – U3.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	27.00	33.80
	$\varepsilon_{s(GV)} = 0.0284$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0227$	19.32	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0226$	20.71	

Table 4.129 : Deformation capacities and observed damages for collapsing damage – U3.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	33.90	45.00
	$\varepsilon_{s(GÇ)} = 0.0358$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0303$	25.76	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0301$	27.48	

4.2.25 Specimen U4 (Saatcioglu and Ozcebe)

The observed damages reported by Saatcioglu and Ozcebe (1989) and the performance limits proposed by seismic codes are given in following **Table 4.130**, **Table 4.131** and **Table 4.132** for three damage limits.

Table 4.130 : Deformation capacities and observed damages for minimum damage – U4.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	7.88	13.06
	$\varepsilon_{s(MN)} = 0.0060$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0108$	9.10	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0048$	4.44	

Table 4.131 : Deformation capacities and observed damages for significant damage – U4.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	29.31	48.80
	$\varepsilon_{s(GV)} = 0.0317$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0309$	26.02	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0284$	25.98	

Table 4.132 : Deformation capacities and observed damages for collapsing damage – U4.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	38.01	65.00
	$\varepsilon_{s(GÇ)} = 0.0415$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0412$	34.69	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0379$	34.63	

4.2.26 Specimen U6 (Saatcioglu and Ozcebe)

The observed damages reported by Saatcioglu and Ozcebe (1989) and the performance limits proposed by seismic codes are given in following **Table 4.133**, **Table 4.134** and **Table 4.135** for three damage limits.

Table 4.133 : Deformation capacities and observed damages for minimum damage – U6.

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	8.10	13.58
	$\varepsilon_{s(MN)} = 0.0068$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0097$	8.30	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0049$	4.48	

Table 4.134 : Deformation capacities and observed damages for significant damage – U6.

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	30.39	51.00
	$\varepsilon_{s(GV)} = 0.0337$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0375$	31.90	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0285$	26.05	

Table 4.135 : Deformation capacities and observed damages for collapsing damage – U6.

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	36.20	68.00
	$\varepsilon_{s(GÇ)} = 0.0392$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0500$	42.54	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0382$	34.87	

4.2.27 Specimen U7 (Saatcioglu and Ozcebe)

The observed damages reported by Saatcioglu and Ozcebe (1989) and the performance limits proposed by seismic codes are given in following **Table 4.136**, **Table 4.137** and **Table 4.138** for three damage limits.

Table 4.136 : Deformation capacities and observed damages for minimum damage – U7.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	8.31	13.61
	$\varepsilon_{s(MN)} = 0.0071$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0096$	8.24	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0049$	4.50	

Table 4.137 : Deformation capacities and observed damages for significant damage – U7.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$	30.95	48.00
	$\varepsilon_{s(GV)} = 0.0348$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0371$	31.65	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0287$	26.25	

Table 4.138 : Deformation capacities and observed damages for collapsing damage – U7.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$	37.51	64.00
	$\varepsilon_{s(GÇ)} = 0.0415$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0495$	42.20	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0385$	35.16	

4.2.28 Specimen No.5 (Tanaka)

The observed damages reported by Tanaka (1990) and the performance limits proposed by seismic codes are given in following **Table 4.139**, **Table 4.140** and **Table 4.141** for three damage limits.

Table 4.139 : Deformation capacities and observed damages for minimum damage – No.5.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	17.06	13.55
	$\varepsilon_{s(MN)} = 0.0107$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0088$	13.00	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0050$	7.56	

Table 4.140 : Deformation capacities and observed damages for significant damage – No.5.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0096$	-	22.00
	$\varepsilon_{s(GV)} = 0.0400$	52.54	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0389$	57.14	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0282$	42.67	

Table 4.141 : Deformation capacities and observed damages for collapsing damage – No.5.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0163$	76.34	46.00
	$\varepsilon_{s(GÇ)} = 0.0598$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0518$	76.18	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0379$	57.39	

4.2.29 Specimen No.6 (Tanaka)

The observed damages reported by Tanaka (1990) and the performance limits proposed by seismic codes are given in following **Table 4.142**, **Table 4.143** and **Table 4.144** for three damage limits.

Table 4.142 : Deformation capacities and observed damages for minimum damage – No.6.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	17.06	11.96
	$\varepsilon_{s(MN)} = 0.0107$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0088$	13.00	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0050$	7.56	

Table 4.143 : Deformation capacities and observed damages for significant damage – No.6.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0096$	52.54	19.00
	$\varepsilon_{s(GV)} = 0.0400$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0389$	57.14	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0282$	42.67	

Table 4.144 : Deformation capacities and observed damages for collapsing damage – No.6.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0163$	76.34	32.00
	$\varepsilon_{s(GÇ)} = 0.0598$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0518$	76.18	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0379$	57.39	

4.2.30 Specimen No.7 (Tanaka)

The observed damages reported by Tanaka (1990) and the performance limits proposed by seismic codes are given in following **Table 4.145**, **Table 4.146** and **Table 4.147** for three damage limits.

Table 4.145 : Deformation capacities and observed damages for minimum damage – No.7.

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	11.45	9.68
	$\varepsilon_{s(MN)} = 0.0044$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0086$	12.70	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0045$	6.83	

Table 4.146 : Deformation capacities and observed damages for significant damage – No.7.

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0106$	31.03	19.00
	$\varepsilon_{s(GV)} = 0.0170$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0255$	37.48	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0231$	35.07	

Table 4.147 : Deformation capacities and observed damages for collapsing damage – No.7.

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0140$	39.09	29.00
	$\varepsilon_{s(GÇ)} = 0.0222$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0340$	49.97	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0299$	45.27	

4.2.31 Specimen No.8 (Tanaka)

The observed damages reported by Tanaka (1990) and the performance limits proposed by seismic codes are given in following **Table 4.148**, **Table 4.149** and **Table 4.150** for three damage limits.

Table 4.148 : Deformation capacities and observed damages for minimum damage – No.8.

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages
			Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$	11.45	8.39
	$\varepsilon_{s(MN)} = 0.0044$	-	
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0086$	12.70	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0045$	6.83	

Table 4.149 : Deformation capacities and observed damages for significant damage – No.8.

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages
			Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0106$	31.03	13.00
	$\varepsilon_{s(GV)} = 0.0170$	-	
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0255$	37.48	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0231$	35.07	

Table 4.150 : Deformation capacities and observed damages for collapsing damage – No.8.

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages
			Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0140$	39.09	25.00
	$\varepsilon_{s(GÇ)} = 0.0222$	-	
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0340$	49.97	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0299$	45.27	

4.2.32 Specimen A2 (Wehbe et al.)

The observed damages reported by Wehbe et al. (1998) and the performance limits proposed by seismic codes are given in following **Table 4.151**, **Table 4.152** and **Table 4.153** for three damage limits.

Table 4.151 : Deformation capacities and observed damages for minimum damage – A2.

Seismic Codes	Limit Conditions	Minimum Damage Limits	Observed Damages Yielding
		(mm)	(mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$ $\varepsilon_{s(MN)} = 0.0067$	24.27 -	22.00
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0125$	23.48	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0042$	7.95	

Table 4.152 : Deformation capacities and observed damages for significant damage – A2.

Seismic Codes	Limit Conditions	Significant Damage Limits	Observed Damages Concrete Crushing
		(mm)	(mm)
TSC	$\varepsilon_{cu(GV)} = 0.0068$ $\varepsilon_{s(GV)} = 0.02140$	41.98 -	40.00
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0177$	33.19	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0154$	29.22	

Table 4.153 : Deformation capacities and observed damages for collapsing damage – A2.

Seismic Codes	Limit Conditions	Collapsing Damage Limits	Observed Damages Significant Concrete Spalling
		(mm)	(mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0086$ $\varepsilon_{s(GÇ)} = 0.0174$	49.47 -	62.00
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0236$	44.25	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0207$	39.42	

4.2.33 Specimen B2 (Wehbe et al.)

The observed damages reported by Wehbe et al. (1998) and the performance limits proposed by seismic codes are given in following **Table 4.154**, **Table 4.155** and **Table 4.156** for three damage limits.

Table 4.154 : Deformation capacities and observed damages for minimum damage – B2.

Seismic Codes	Limit Conditions	Minimum Damage Limits (mm)	Observed Damages: Yielding (mm)
TSC	$\varepsilon_{cu(MN)} = 0.0035$ $\varepsilon_{s(MN)} = 0.0058$	24.07 -	26.86
Eurocode	Chord Rotation $\theta_{DL(radyan)} = 0.0129$	24.20	
ASCE	Chord Rotation $\theta_{DL(radyan)} = 0.0044$	8.45	

Table 4.155 : Deformation capacities and observed damages for significant damage – B2.

Seismic Codes	Limit Conditions	Significant Damage Limits (mm)	Observed Damages: Concrete Crushing (mm)
TSC	$\varepsilon_{cu(GV)} = 0.0135$ $\varepsilon_{s(GV)} = 0.0300$	67.32 -	53.00
Eurocode	Chord Rotation $\theta_{SD(radyan)} = 0.0366$	68.57	
ASCE	Chord Rotation $\theta_{SD(radyan)} = 0.0210$	40.00	

Table 4.156 : Deformation capacities and observed damages for collapsing damage – B2.

Seismic Codes	Limit Conditions	Collapsing Damage Limits (mm)	Observed Damages: Significant Concrete Spalling (mm)
TSC	$\varepsilon_{cu(GÇ)} = 0.0180$ $\varepsilon_{s(GÇ)} = 0.0392$	84.18 -	74.00
Eurocode	Chord Rotation $\theta_{NC(radyan)} = 0.0488$	91.43	
ASCE	Chord Rotation $\theta_{NC(radyan)} = 0.0278$	52.93	

5. EVALUATION OF SPECIMEN PERFORMANCES

In this study, ductile concrete columns with different properties, and under reversed and cycling lateral load effects, by using Turkish Seismic Code 2007, Eurocode 8 and ASCE/SEI 41, are compared in terms of seismic performance assessment. The predictions of the methods given in the codes are compared with each other as well as the experimental results. Similarities between the predictions of the methods given in the codes and experimental results and also differences between the codes are displayed by this comparison.

5.1 Minimum Damage Limit

Minimum damage limits are calculated for each given codes in Section 4 and all performance limits of specimens are given comparatively in this section. According to the comparison of analysis results of specimen and observed damage limits, the predictions of Turkish Seismic Code are close to yielding limit of specimens and the predictions of ASCE/SEI are approximately half of calculated values but Eurocode provides higher values for performance limits of specimens.

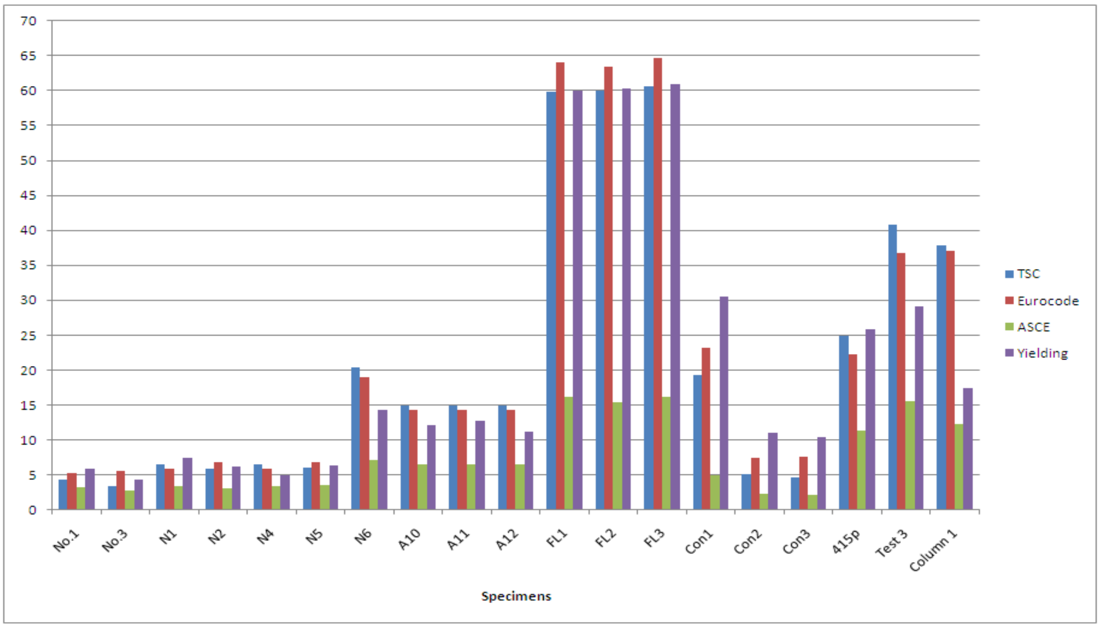

Figure 5.1 : Minimum damage limits given in codes and observed yielding damages for circular columns.

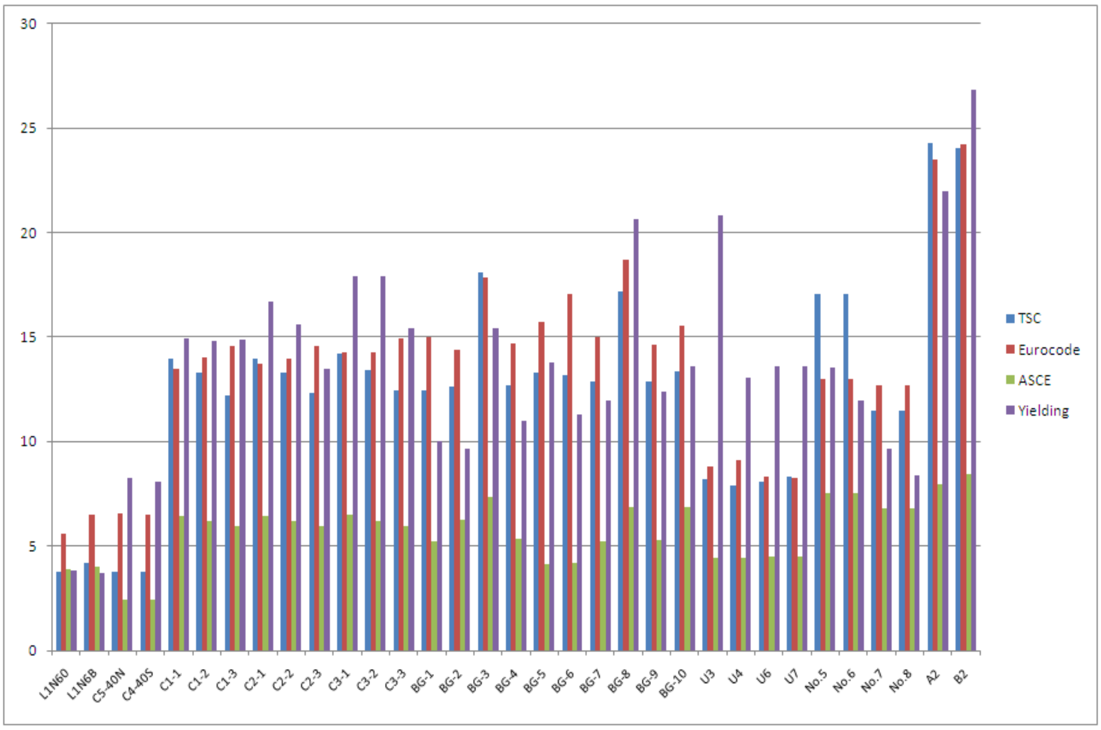

Figure 5.2 : Minimum damage limits given in codes and observed yielding damages for rectangular columns.

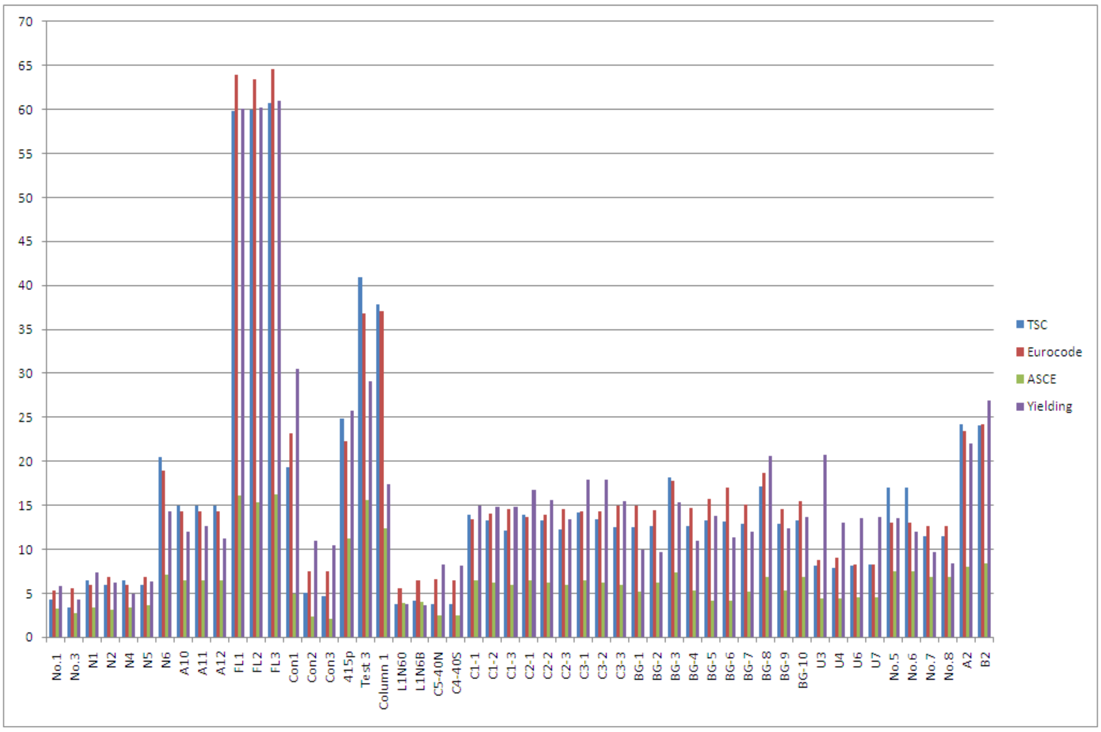

Figure 5.3 : Minimum damage limits given in codes and observed yielding damages for overall.

The minimum damage limits proposed by seismic codes are given in **Figure 5.1, Figure 5.2** and **Figure 5.3** comparatively. The structural performance limits can be put in order from maximum to minimum such as Eurocode, TSC and ASCE.

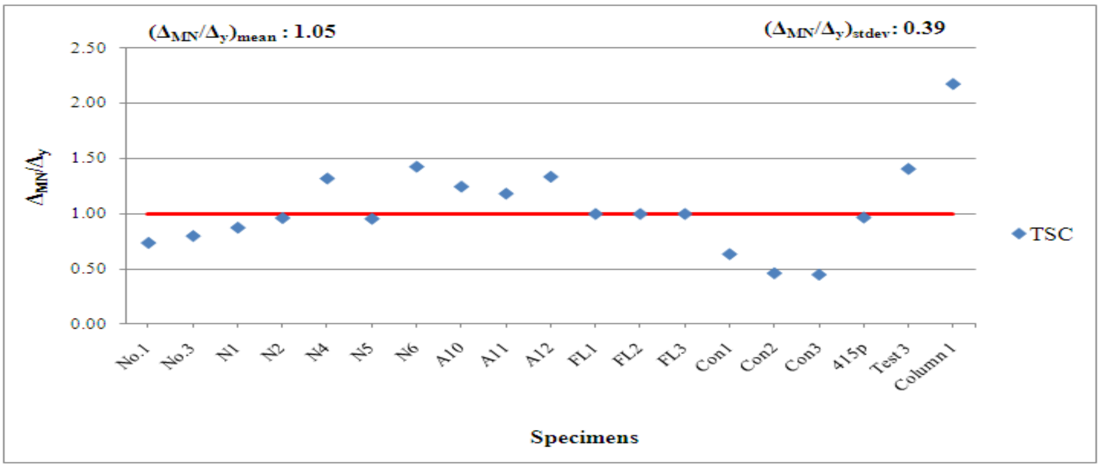

Figure 5.4 : Exceedance ratios of minimum damage limits according to TSC for circular columns.

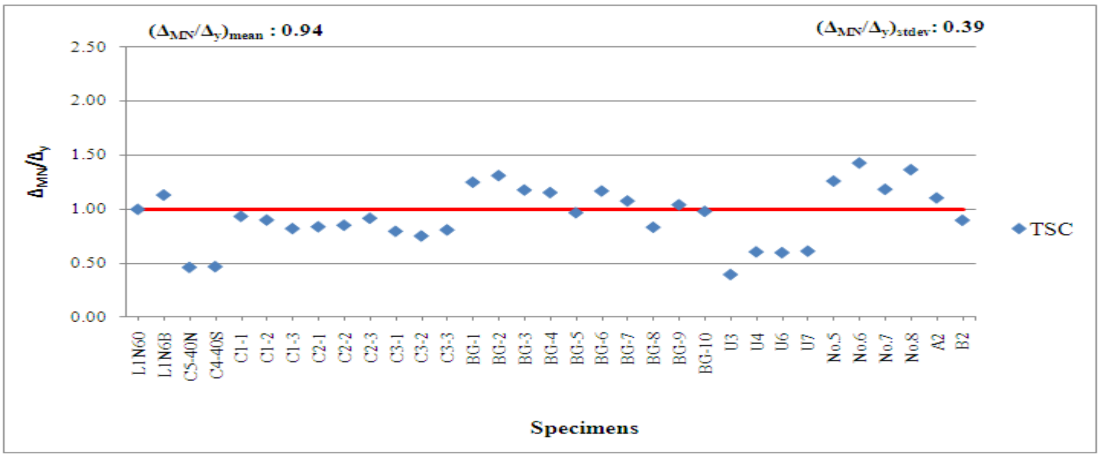

Figure 5.5 : Exceedance ratios of minimum damage limits according to TSC for rectangular columns.

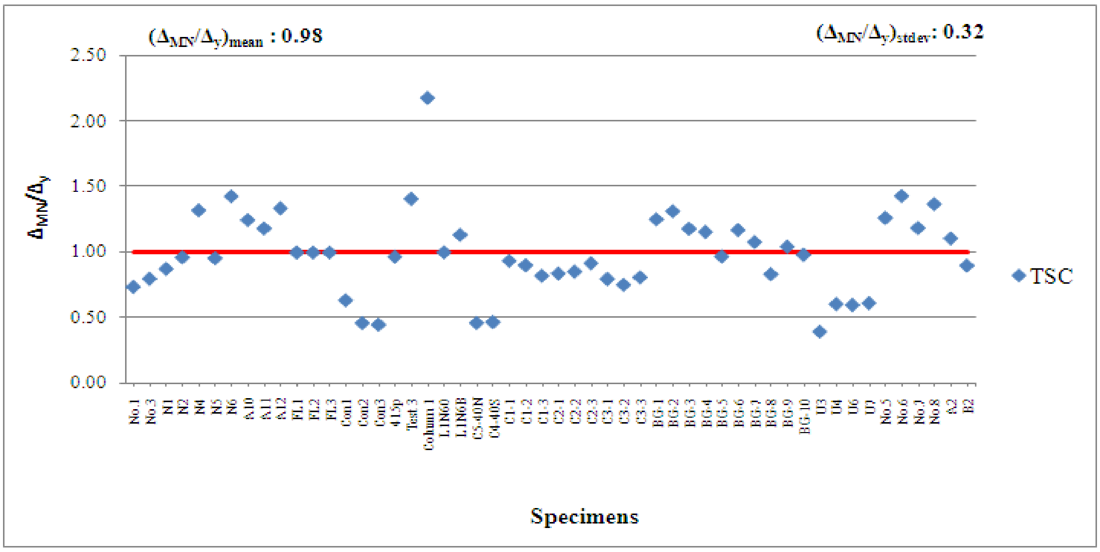

Figure 5.6 : Exceedance ratios of minimum damage limits according to TSC for overall.

The exceedance of minimum damage limits has been reached to 50% percentage for circular and rectangular columns according to Turkish Seismic Code. However, the mean exceedance ratio is 0.98 for overall and the standard deviation of exceedance ratio is 0.32 as given in **Figure 5.4**, **Figure 5.5** and **Figure 5.6**.

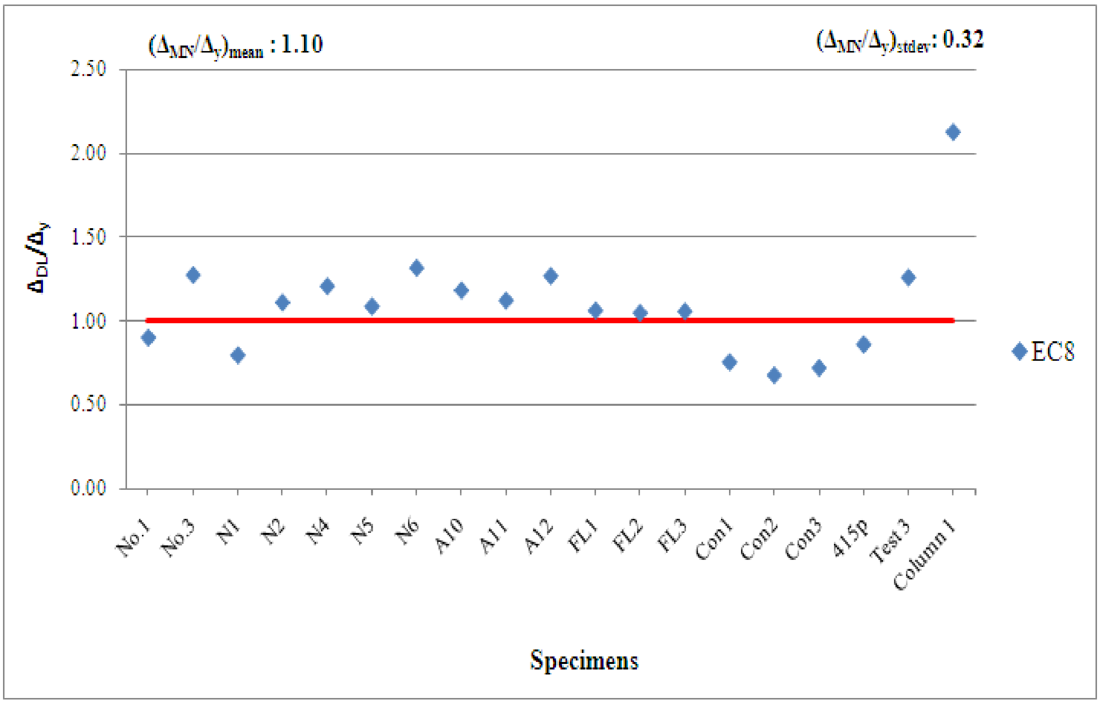

Figure 5.7 : Exceedance ratios of minimum damage limits according to Eurocode for circular columns.

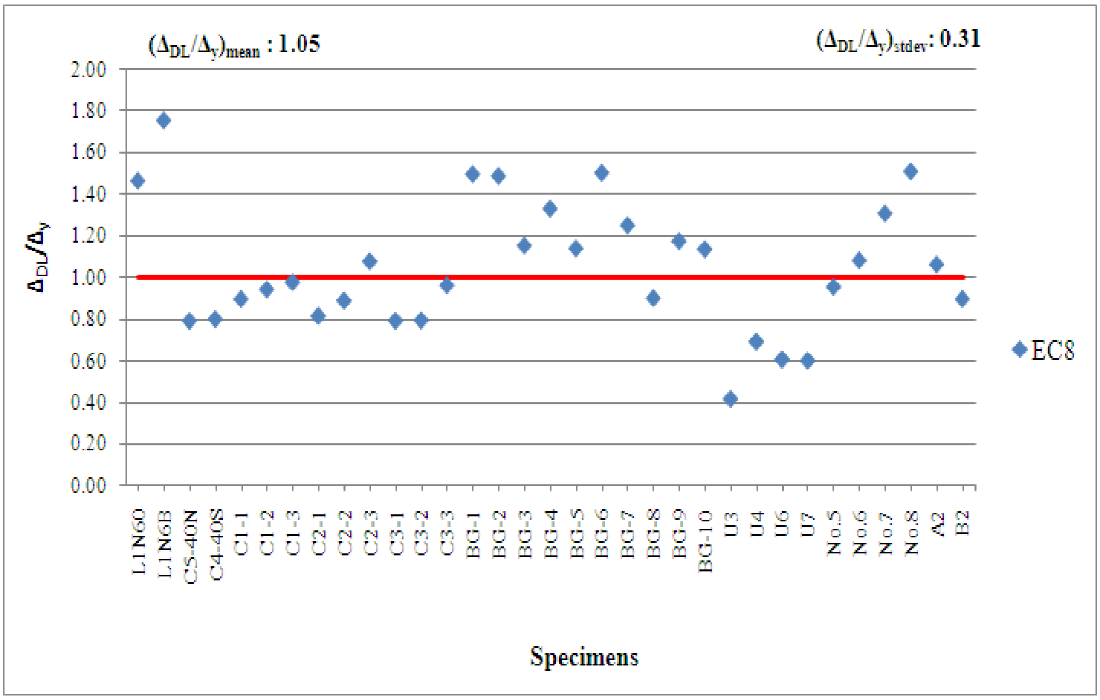

Figure 5.8 : Exceedance ratios of minimum damage limits according to Eurocode for rectangular columns.

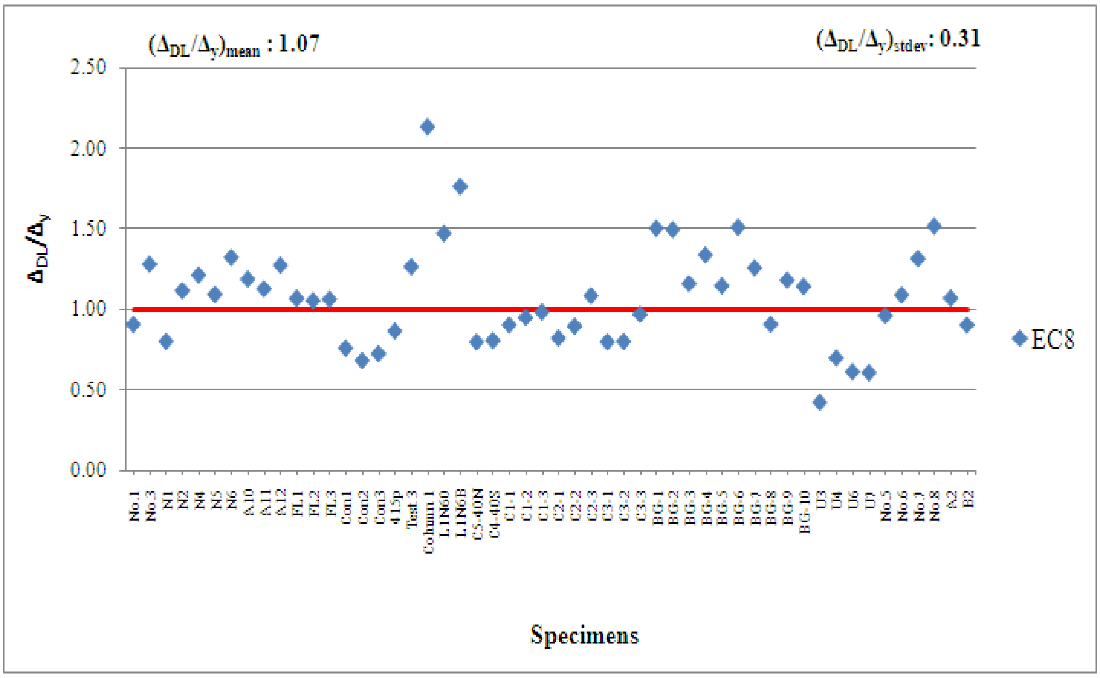

Figure 5.9 : Exceedance ratios of minimum damage limits according to Eurocode for overall.

The exceedance of minimum damage limits has been reached to 36% percentage for circular columns and 100% percentage for rectangular columns according to Eurocode. However, the mean exceedance ratio is 1.11 for overall and the standard deviation of exceedance ratio is 0.33 as given in **Figure 5.7**, **Figure 5.8** and **Figure 5.9**.

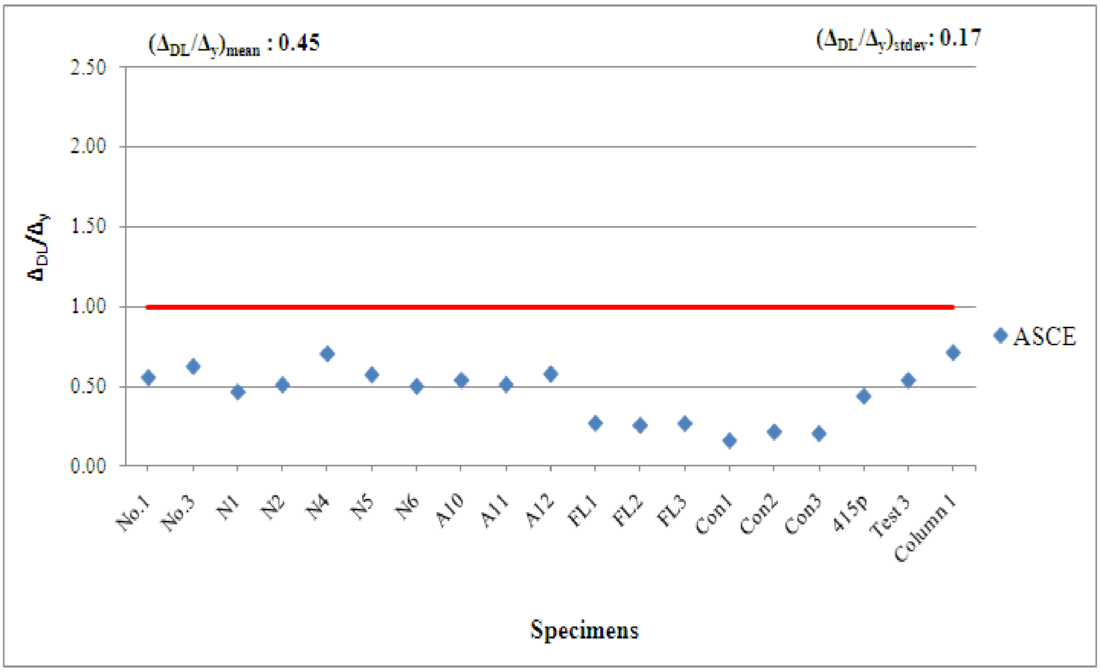

Figure 5.10 : Exceedance ratios of minimum damage limits according to ASCE for circular columns.

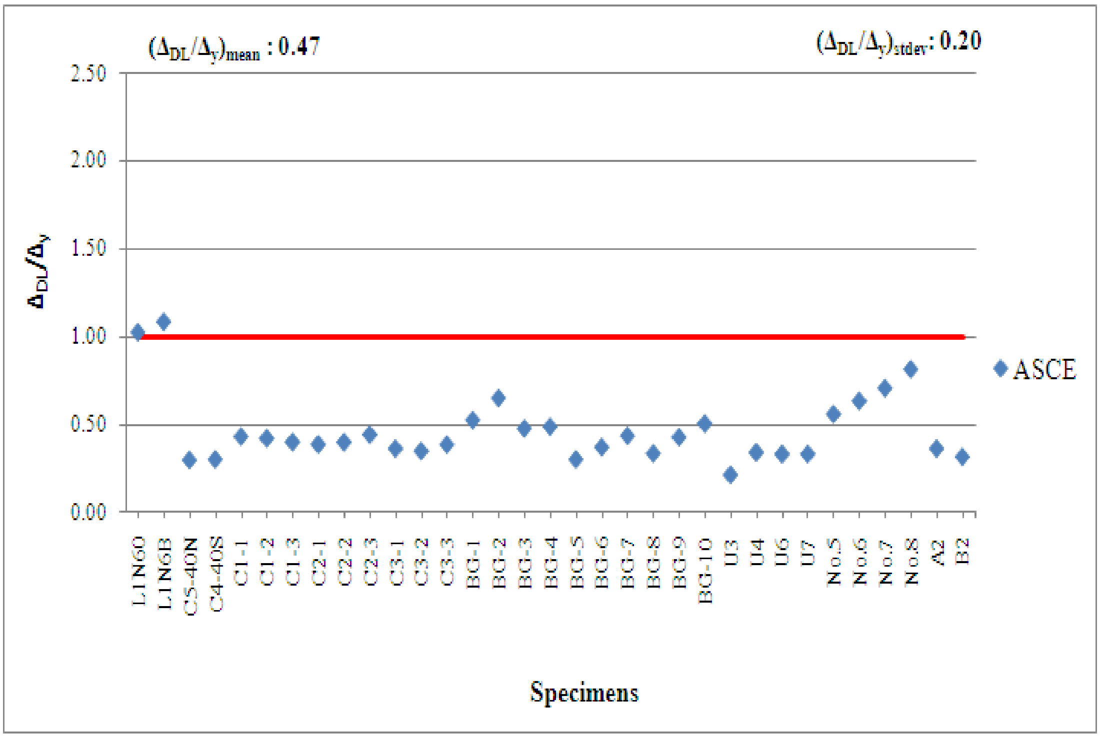

Figure 5.11 : Exceedance ratios of minimum damage limits according to ASCE for rectangular columns.

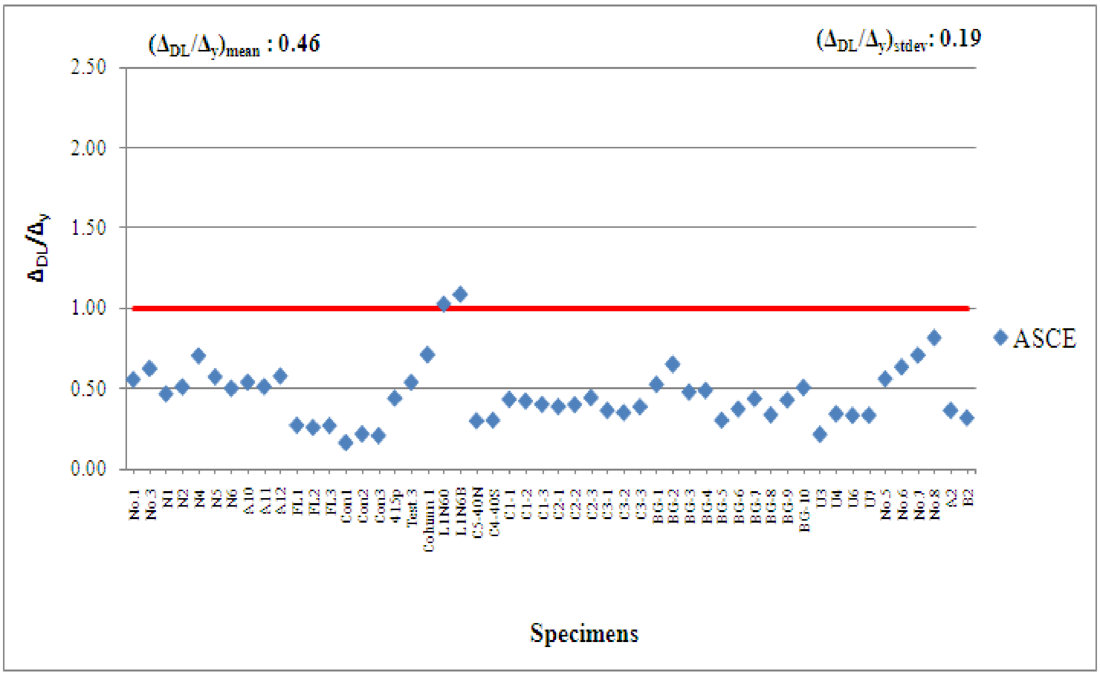

Figure 5.12 : Exceedance ratios of minimum damage limits according to ASCE for overall.

The exceedance of minimum damage limits has been reached to 80% percentage for circular columns and rectangular columns according to ASCE. However, the mean exceedance ratio is 0.46 for overall and the standard deviation of exceedance ratio is 0.19 as given in **Figure 5.10**, **Figure 5.11** and **Figure 5.12**.

According to minimum damage limits proposed by Turkish Seismic Code, 26% percentage of circular columns and 48% percentage of rectangular columns have been exceeded the minimum damage limits. The observed damages have not been reached to the minimum damage limits for 60% percentage of circular and rectangular columns.

According to minimum damage limits proposed by Eurocode, 47% percentage of circular columns and 57% percentage of rectangular columns have been exceeded the minimum damage limits. The observed damages have not been reached to the minimum damage limits for 53% percentage of circular and rectangular columns.

According to minimum damage limits proposed by ASCE, the observed damages have been exceeded the minimum damage limits for almost all circular and rectangular columns.

In conclusion;

- TSC, gives the most consistent results for minimum damage limits. However, the exceedance of observed damages has been reached to 50% percentage.
- Eurocode, the exceedance ratio is close to 1.00 and also the large exceedance ratio has been seen for some specimens. Therefore, the performance limits proposed by Eurocode shall be discussed for structural members.
- ASCE, is in very safety region according to observed damages and also the proposed performance limits are consistent in itself with small standard deviation ratio.

After all these data, TSC is more close to observed damages than Eurocode and ASCE. Eurocode is not exactly safety for structural performance assessments and ASCE is so safety in proposed structural performance limits for specimens.

5.2 Significant Damage Limit

Significant damage limits are calculated for each given codes in Section 4 and all performance limits of specimens are given comparatively in this section. According to the comparison of analysis results of specimen and observed damage limits, the predictions of Turkish Seismic Code and ASCE/SEI are close to concrete crushing limits of specimens but Eurocode provides higher values for performance limits of specimens.

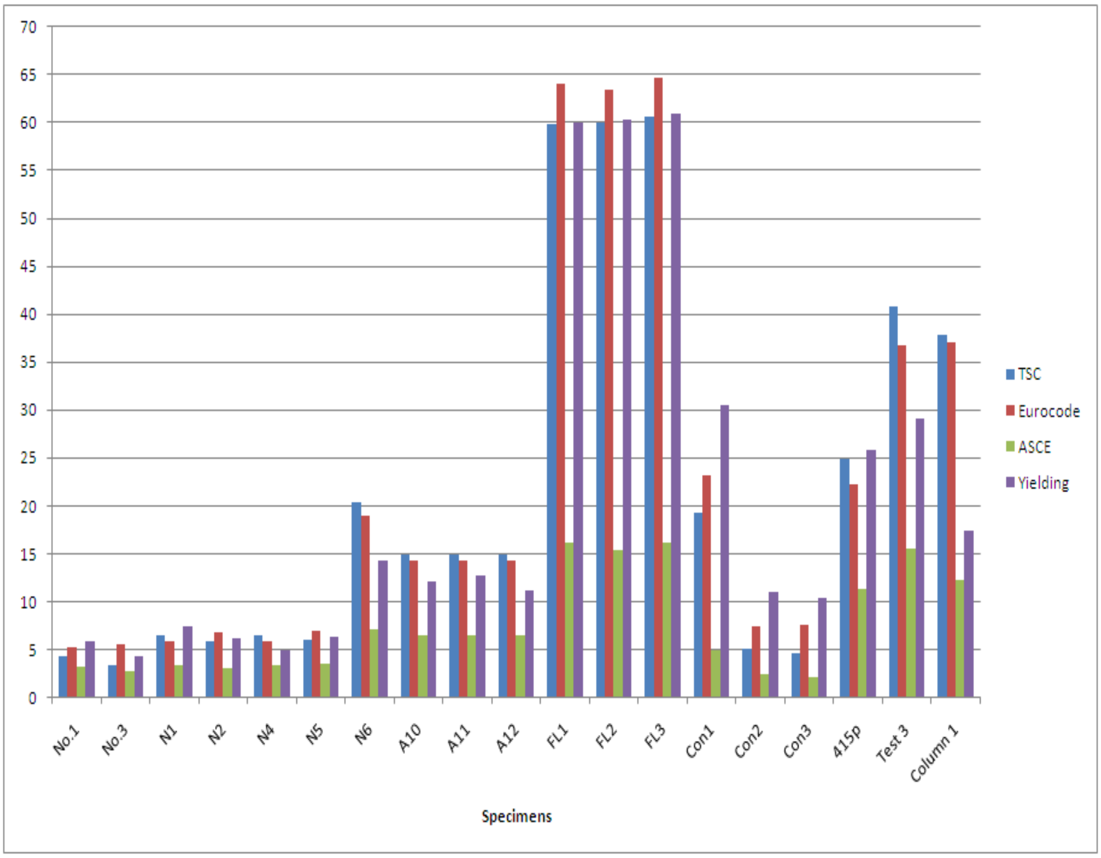

Figure 5.13 : Significant damage limits given in codes and observed concrete crushing damages for circular columns.

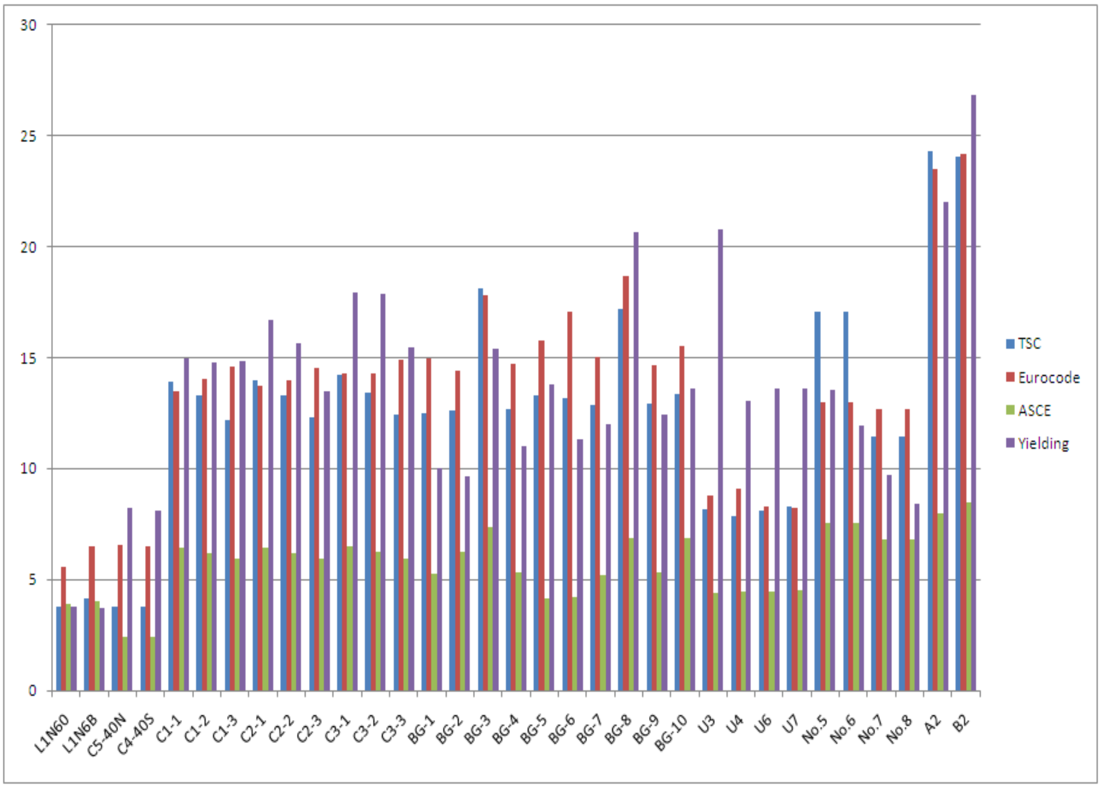

Figure 5.14 : Significant damage limits given in codes and observed concrete crushing damages for rectangular columns.

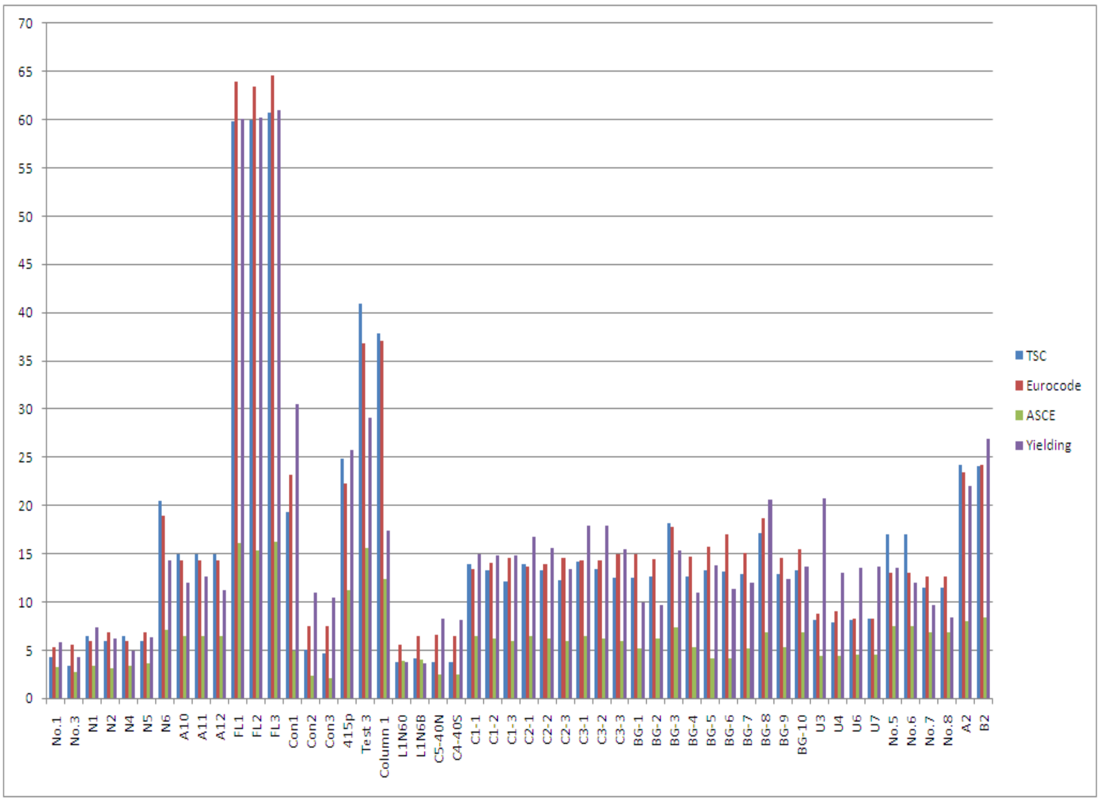

Figure 5.15 : Significant damage limits given in codes and observed concrete crushing damages for overall.

The significant damage limits proposed by seismic codes are given in **Figure 5.13, Figure 5.14** and **Figure 5.15** comparatively. The structural performance limits can be put in order from maximum to minimum such as Eurocode, TSC and ASCE.

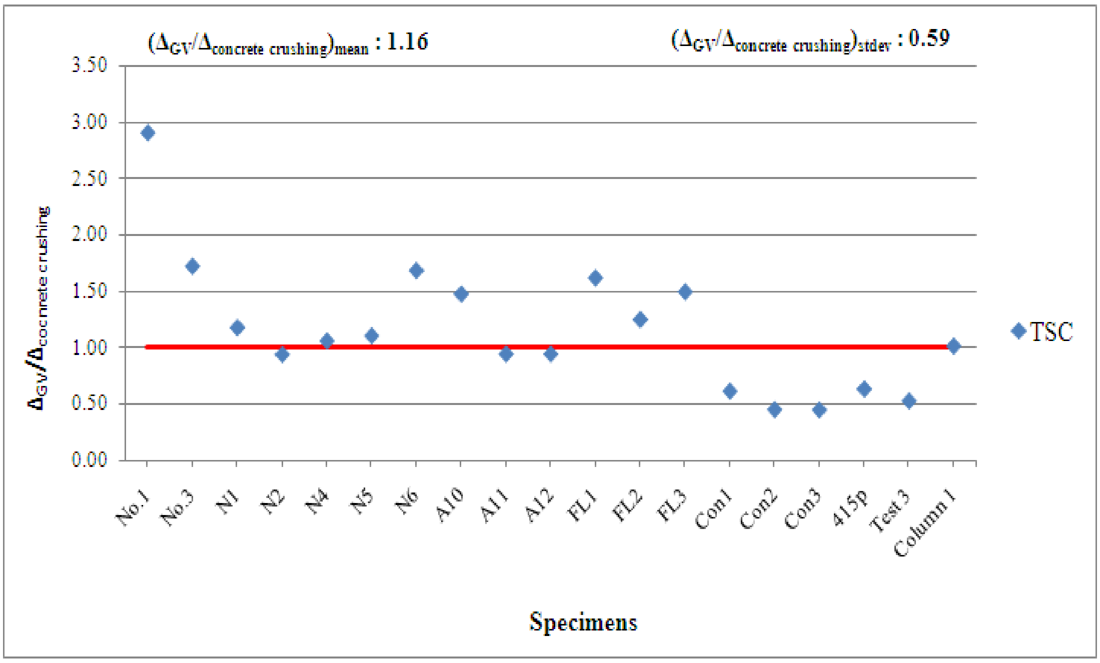

Figure 5.16 : Exceedance ratios of significant damage limits according to TSC for circular columns.

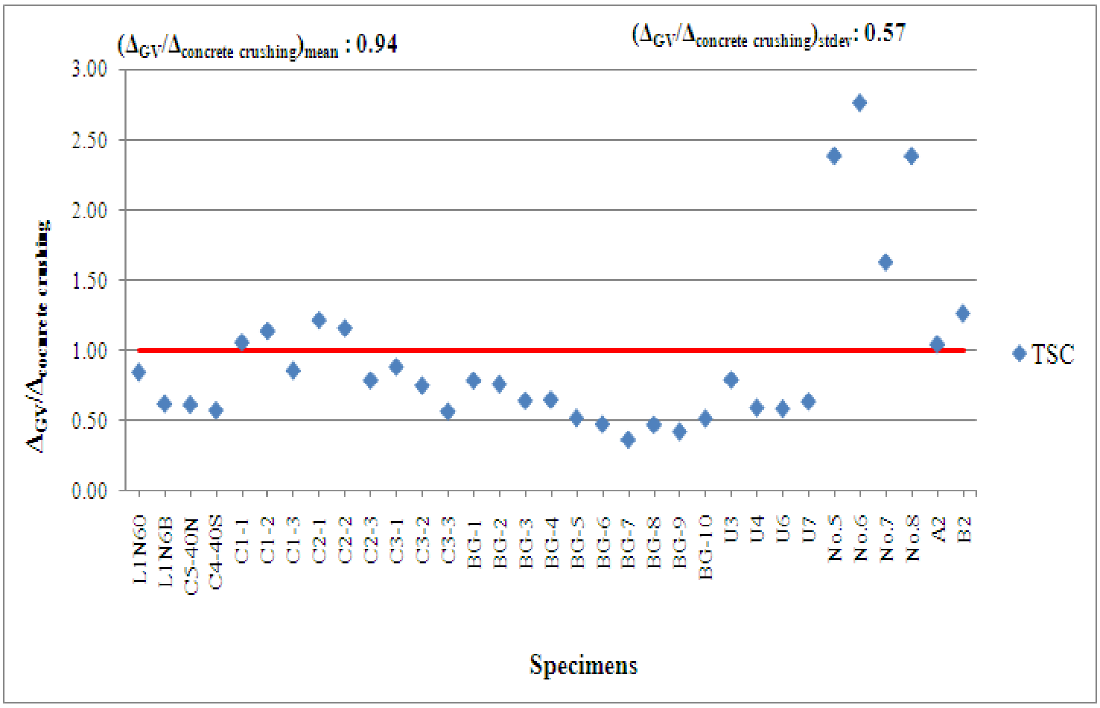

Figure 5.17 : Exceedance ratios of significant damage limits according to TSC for rectangular columns.

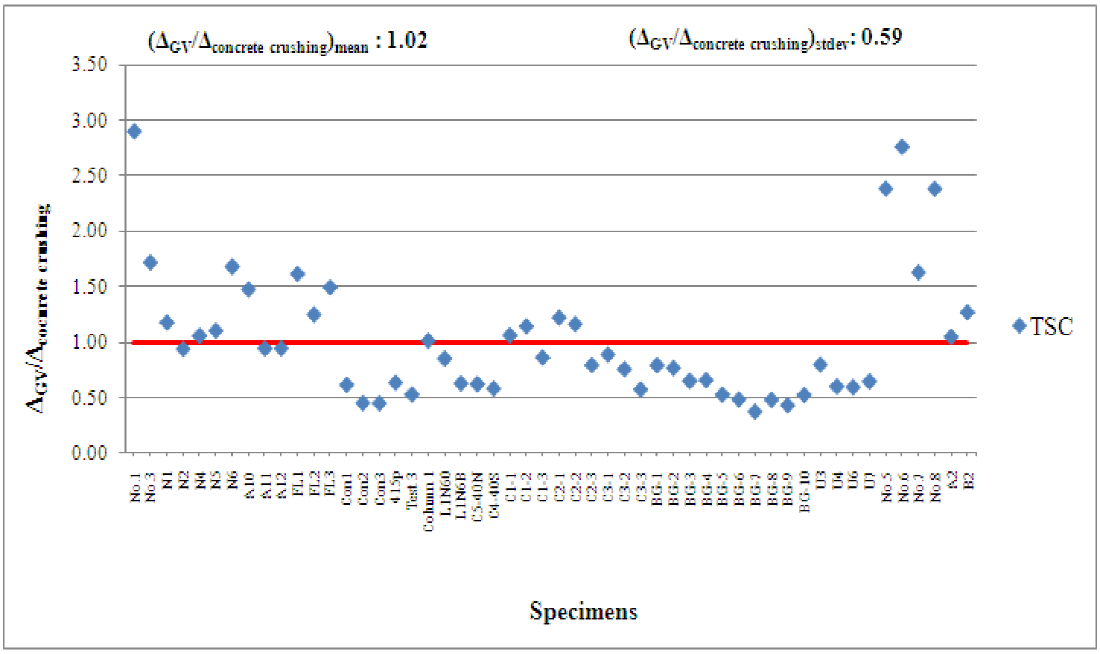

Figure 5.18 : Exceedance ratios of significant damage limits according to TSC for overall.

The exceedance of significant damage limits has been reached to 70% percentage for circular columns and 30% percentage rectangular columns according to Turkish Seismic Code apart from some specimens. However, the mean exceedance ratio is 1.02 for overall and the standard deviation of exceedance ratio is 0.59 as given in **Figure 5.16**, **Figure 5.17** and **Figure 5.18**.

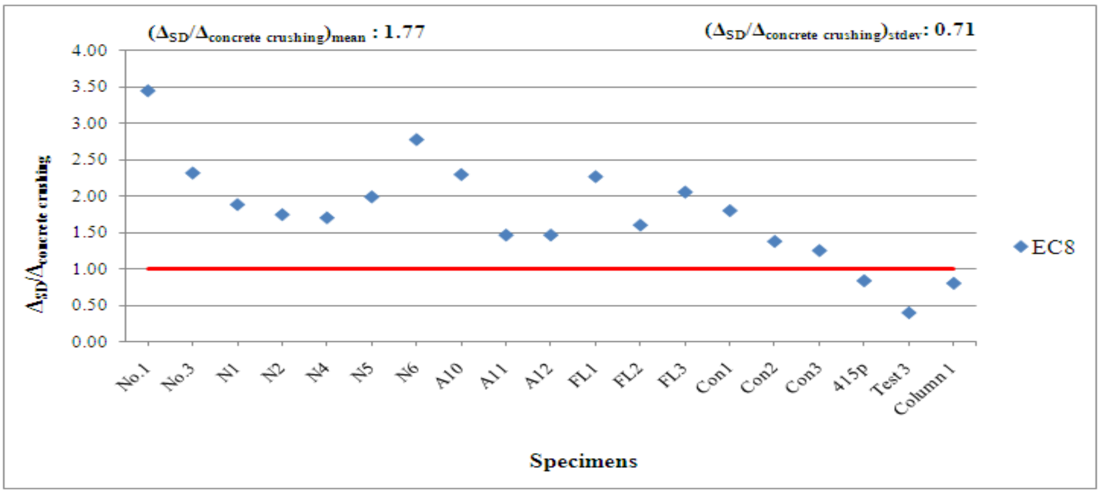

Figure 5.19 : Exceedance ratios of significant damage limits according to Eurocode for circular columns.

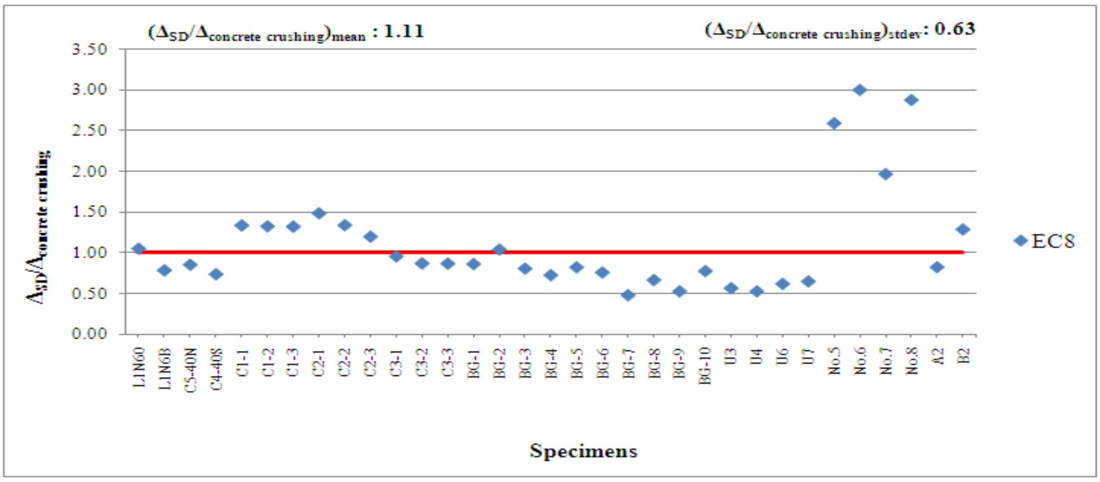

Figure 5.20 : Exceedance ratios of significant damage limits according to Eurocode for rectangular columns.

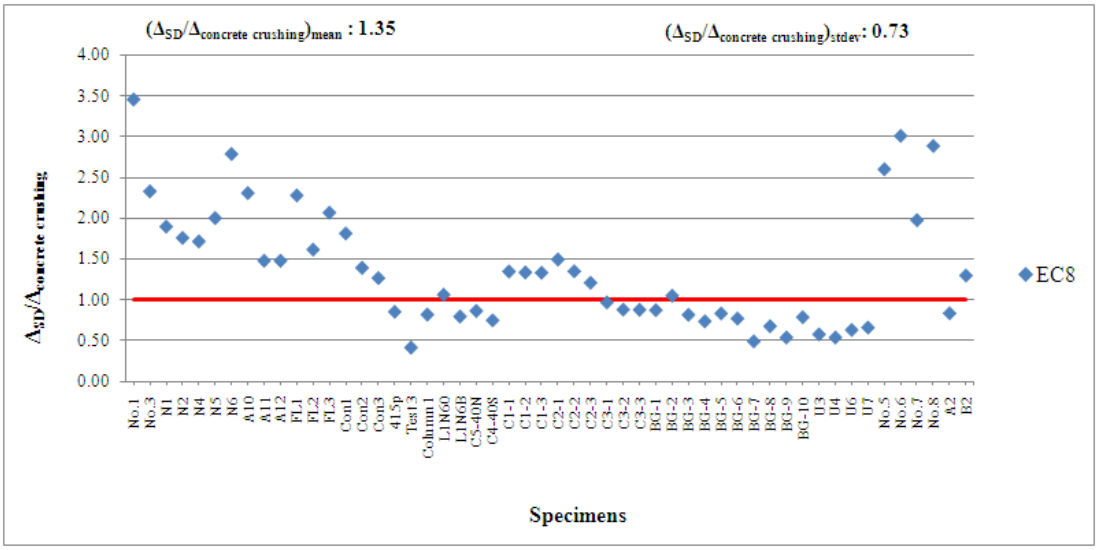

Figure 5.21 : Exceedance ratios of significant damage limits according to Eurocode for overall.

The exceedance of significant damage limits has been reached to 100% percentage for circular columns and 35% percentage rectangular columns according to Eurocode apart from some specimens. However, the mean exceedance ratio is 1.30 for overall and the standard deviation of exceedance ratio is 0.70 as given in **Figure 5.19**, **Figure 5.20** and **Figure 5.21**.

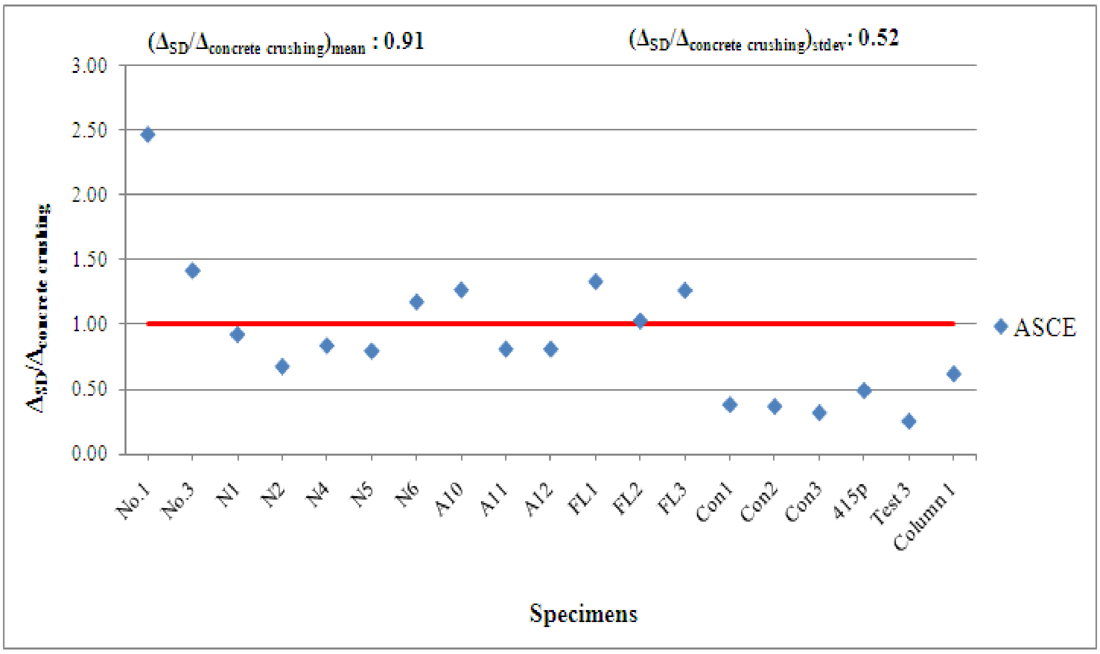

Figure 5.22 : Exceedance ratios of significant damage limits according to ASCE for circular columns.

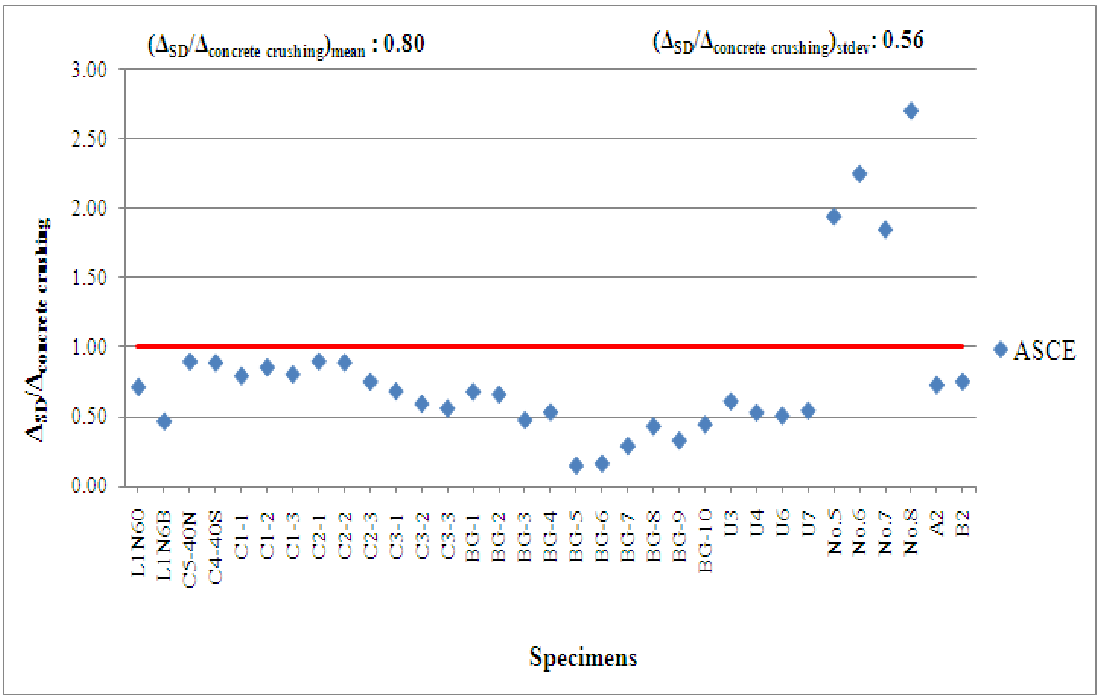

Figure 5.23 : Exceedance ratios of significant damage limits according to ASCE for rectangular columns.

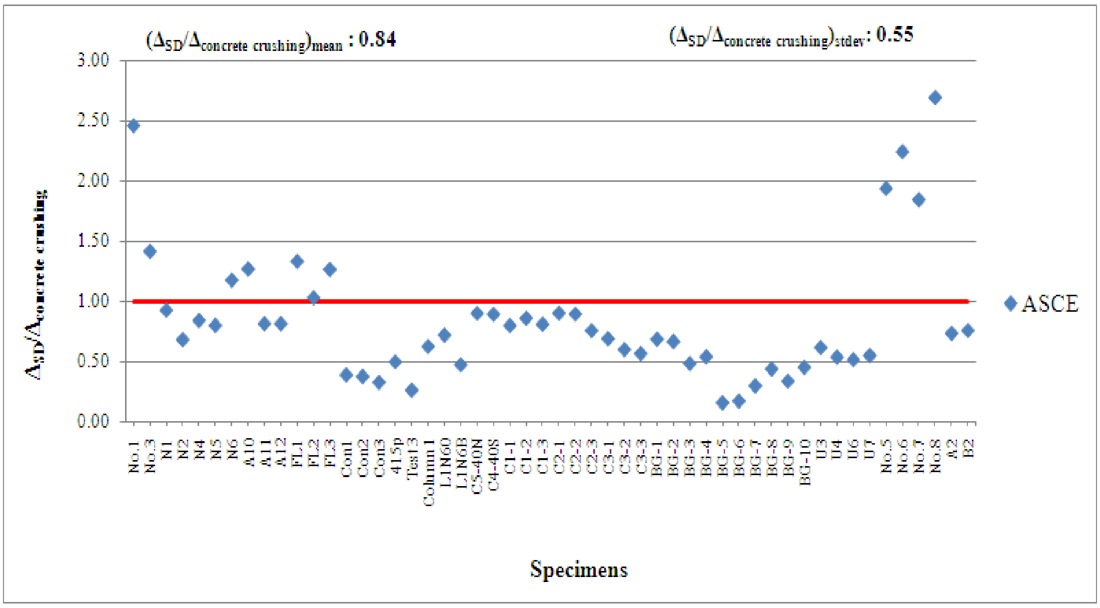

Figure 5.24 : Exceedance ratios of significant damage limits according to ASCE for overall.

The exceedance of significant damage limits has been reached to 40% percentage for circular columns apart from No.1 specimen and there is no exceedance point for apart from specimens such as No.5, No.5, No.7 and No.8 for rectangular columns according to ASCE. However, the mean exceedance ratio is 0.84 for overall and the standard deviation of exceedance ratio is 0.55 as given in **Figure 5.22**, **Figure 5.23** and **Figure 5.24**.

According to significant damage limits proposed by Turkish Seismic Code, 42% percentage of circular columns and 69% percentage of rectangular columns have been exceeded the significant damage limits. The observed damages have not been reached to the significant damage limits for 40% percentage of circular and rectangular columns.

According to significant damage limits proposed by Eurocode, 16% percentage of circular columns and 60% percentage of rectangular columns have been exceeded the significant damage limits. The observed damages have not been reached to the significant damage limits for 56% percentage of circular and rectangular columns.

According to significant damage limits proposed by ASCE, the observed damages have been exceeded the significant damage limits for almost rectangular columns and 63% percentage of circular columns have been exceeded the significant damage limits. The observed damages have not been reached to the significant damage limits for 37% percentage of circular columns.

In conclusion;

- TSC, gives the most consistent results for significant damage limits. However, the exceedance of observed damages has been reached to 50% percentage.
- Eurocode, the exceedance ratio is close to 1.00 and also the large exceedance ratio has been seen for some specimens. Therefore, the performance limits proposed by Eurocode shall be discussed for structural members.
- ASCE, is in very safety region according to observed damages for rectangular columns but not so safety for circular columns.

After all these data, TSC is more close to observed damages than Eurocode and ASCE. Eurocode is not exactly safety for structural performance assessments and ASCE is so safety in proposed structural performance limits for rectangular specimens but not so safety for circular columns.

5.3 Collapsing Damage Limit

Collapsing damage limits are calculated for each given codes in Section 4 and all performance limits of specimens are given comparatively in this section. According to the comparison of analysis results of specimen and observed damage limits, the predictions of Turkish Seismic Code and ASCE/SEI are lower than significant concrete spalling limits of specimens but Eurocode provides higher values for performance limits of specimens.

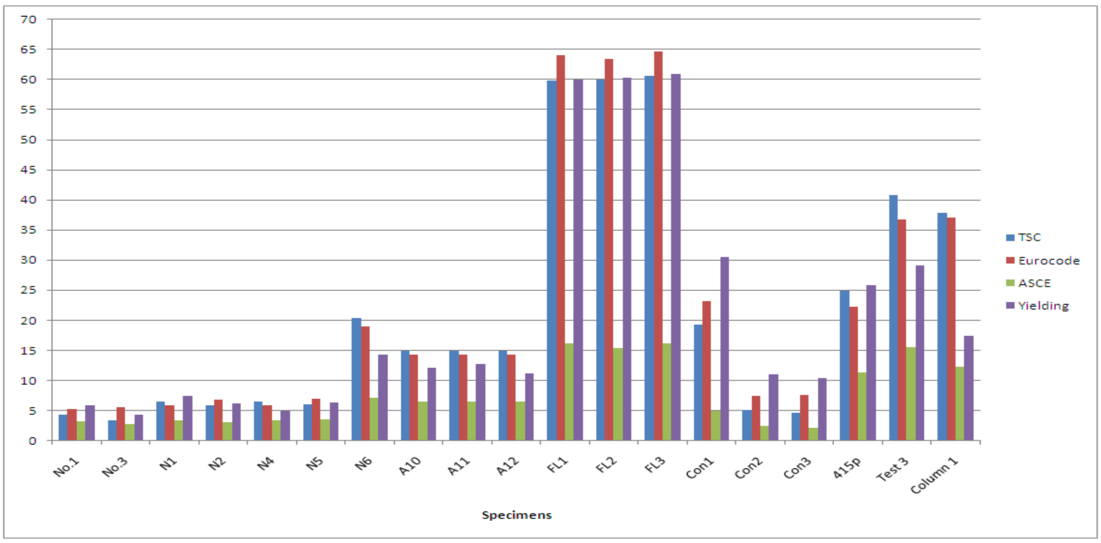

Figure 5.25 : Collapsing damage limits given in codes and observed concrete crushing damages for circular columns.

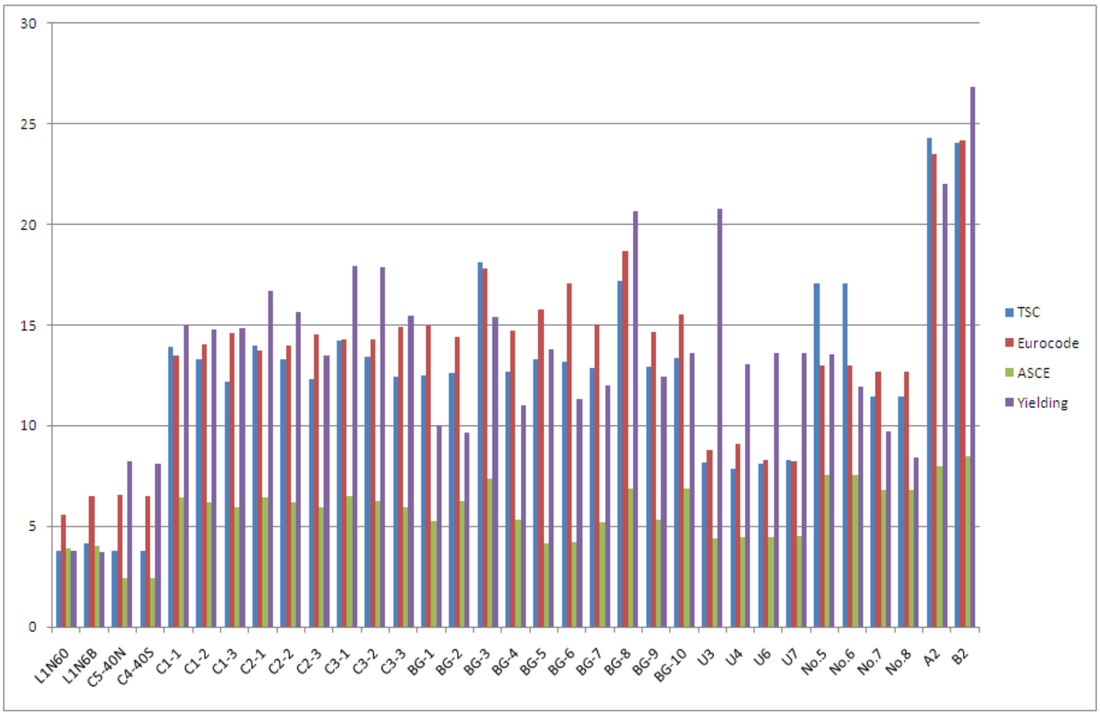

Figure 5.26 : Collapsing damage limits given in codes and observed concrete crushing damages for rectangular columns.

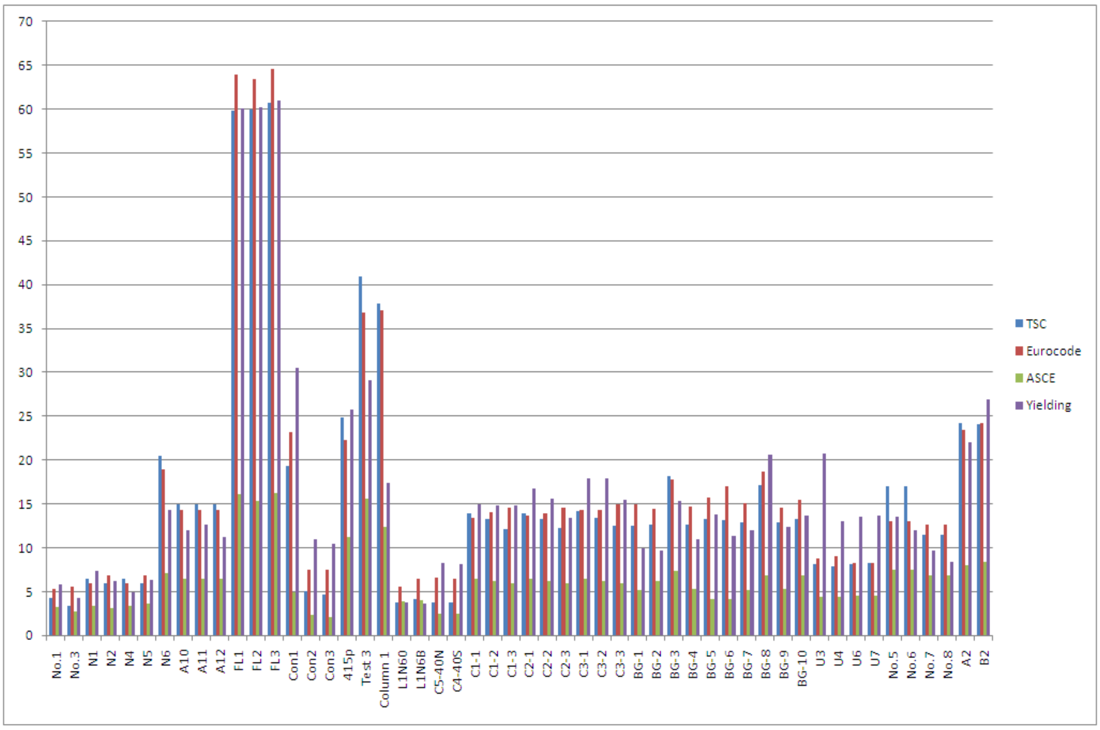

Figure 5.27 : Collapsing damage limits given in codes and observed concrete crushing damages for overall.

The collapsing damage limits proposed by seismic codes are given in **Figure 5.25, Figure 5.26** and **Figure 5.27** comparatively. The structural performance limits can be put in order from maximum to minimum such as Eurocode, TSC and ASCE.

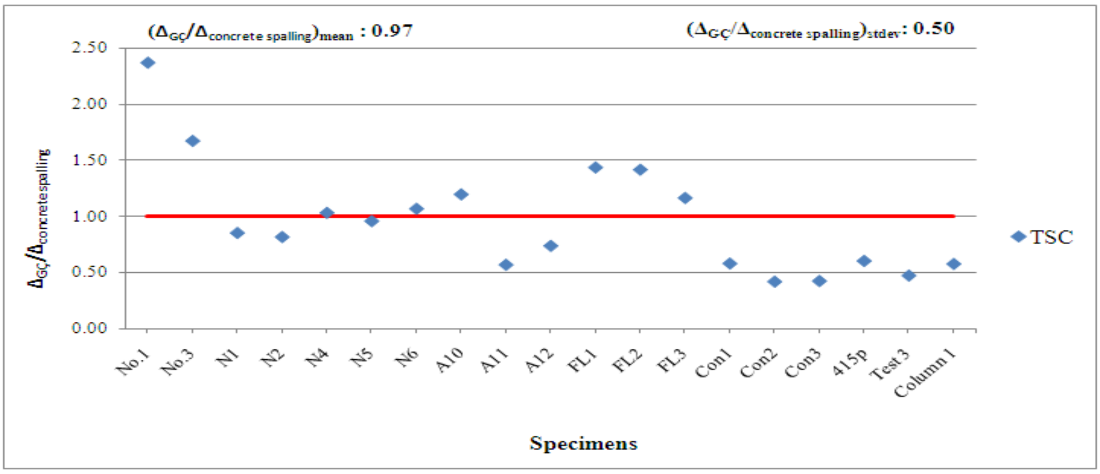

Figure 5.28 : Exceedance ratios of collapsing damage limits according to TSC for circular columns.

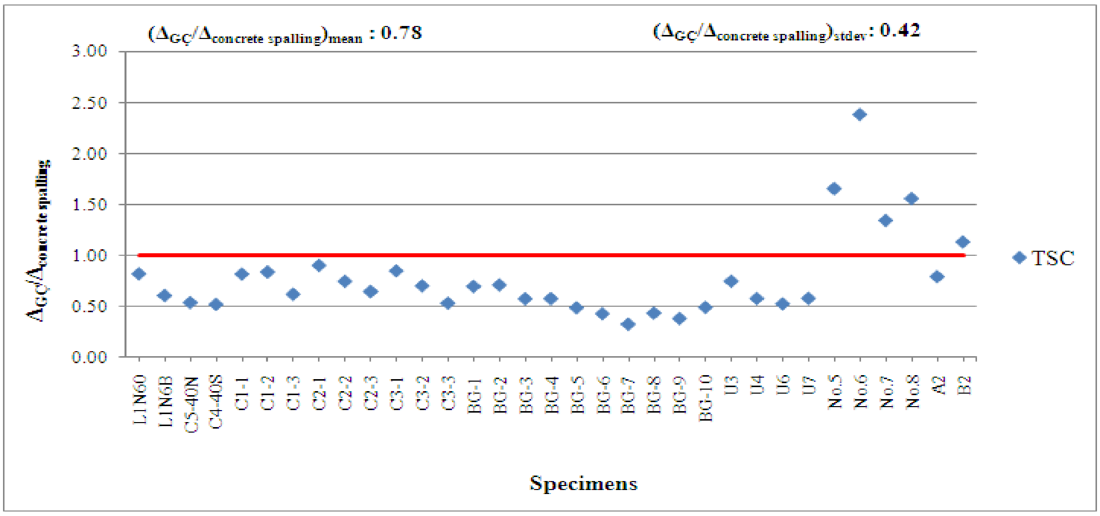

Figure 5.29 : Exceedance ratios of collapsing damage limits according to TSC for rectangular columns.

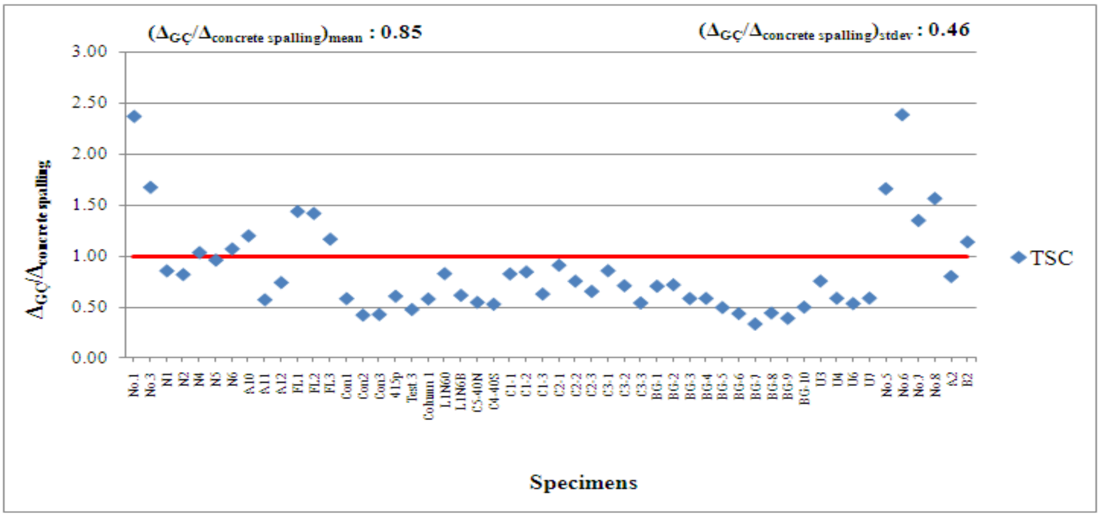

Figure 5.30 : Exceedance ratios of collapsing damage limits according to TSC for overall.

The exceedance of collapsing damage limits has been reached to 70% percentage for circular columns and 60% percentage rectangular columns according to Turkish Seismic Code apart from some specimens. However, the mean exceedance ratio is 0.85 for overall and the standard deviation of exceedance ratio is 0.46 as given in **Figure 5.28**, **Figure 5.29** and **Figure 5.30**.

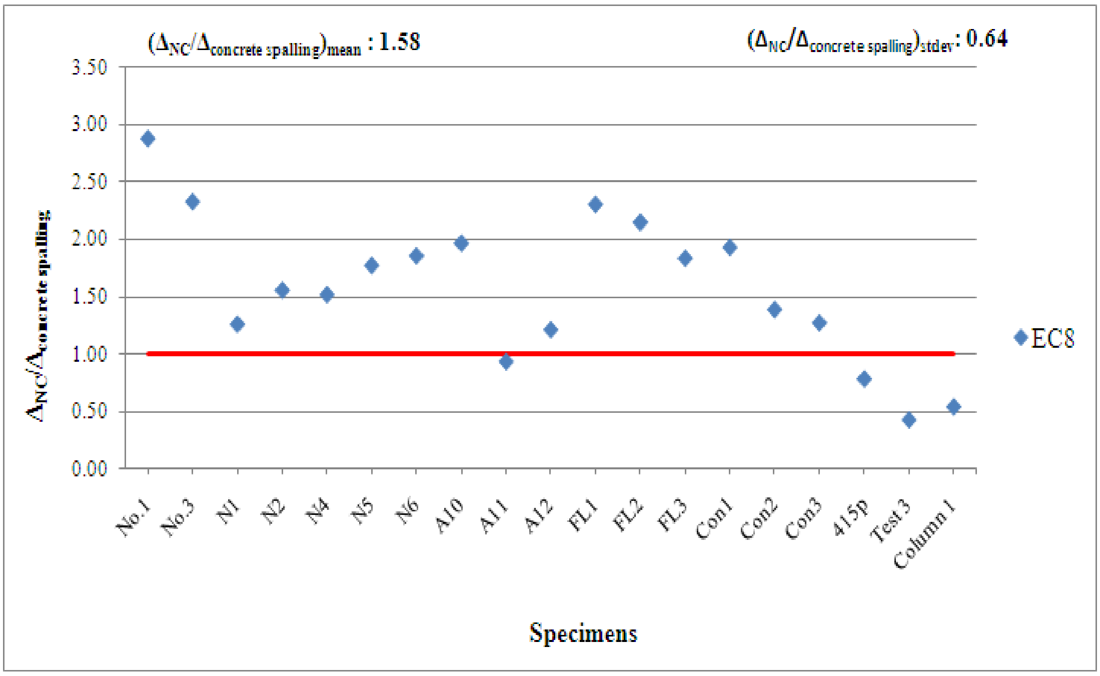

Figure 5.31 : Exceedance ratios of collapsing damage limits according to Eurocode for circular columns.

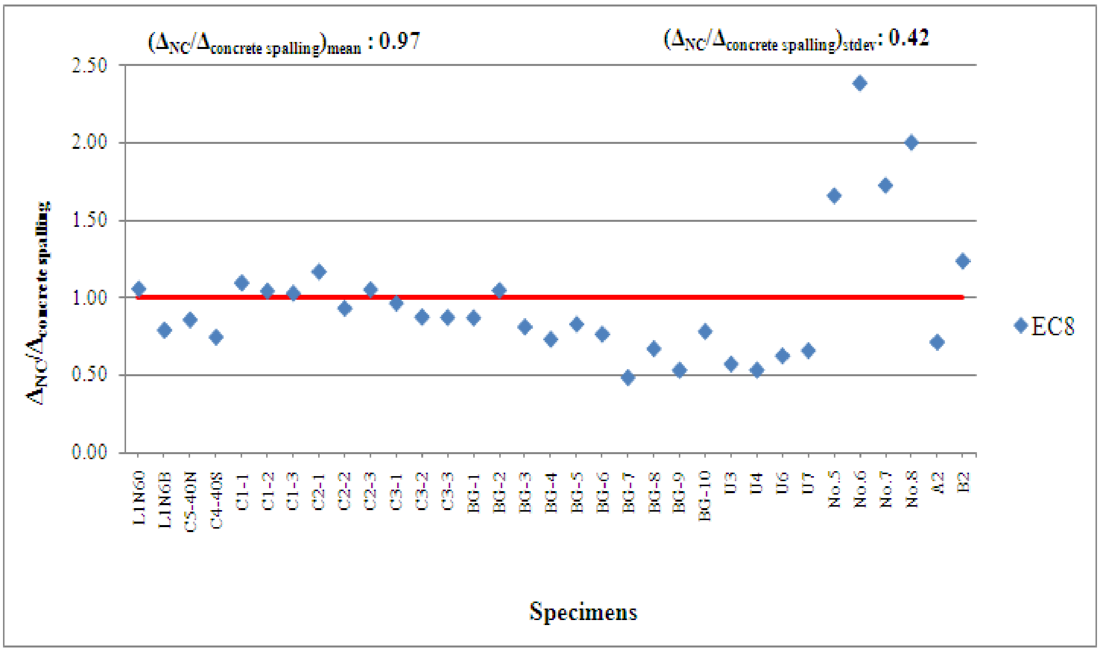

Figure 5.32 : Exceedance ratios of collapsing damage limits according to Eurocode for rectangular columns.

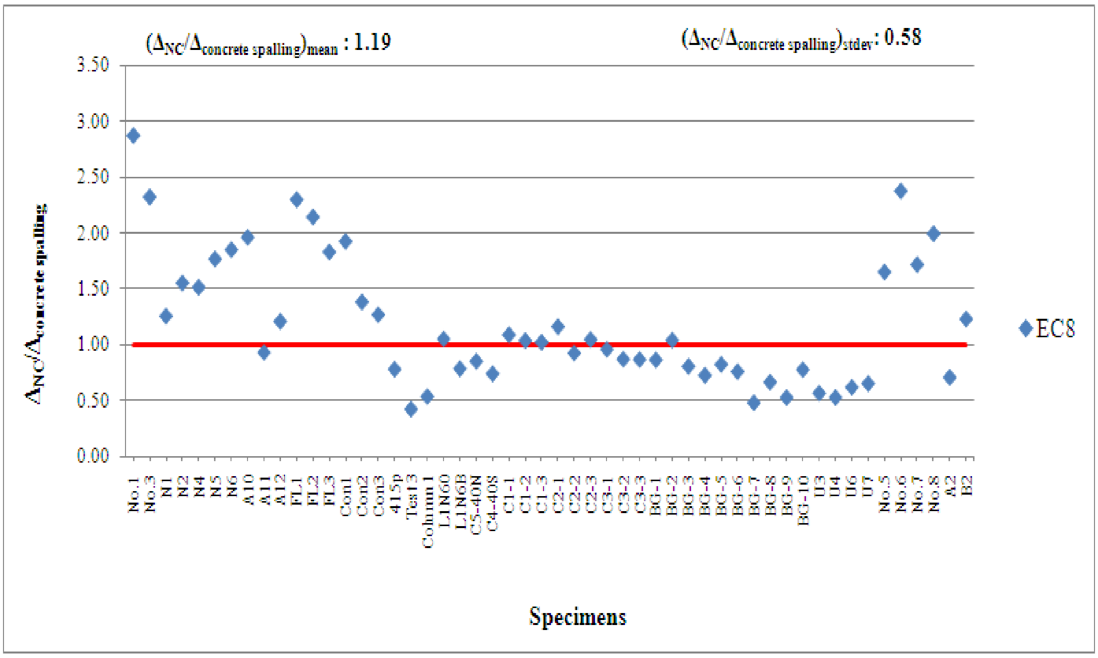

Figure 5.33 : Exceedance ratios of collapsing damage limits according to Eurocode for overall.

The exceedance of collapsing damage limits has been reached to 100% percentage for circular columns and 60% percentage rectangular columns according to Eurocode apart from some specimens. However, the mean exceedance ratio is 1.14 for overall and the standard deviation of exceedance ratio is 0.57 as given in **Figure 5.31**, **Figure 5.32** and **Figure 5.33**.

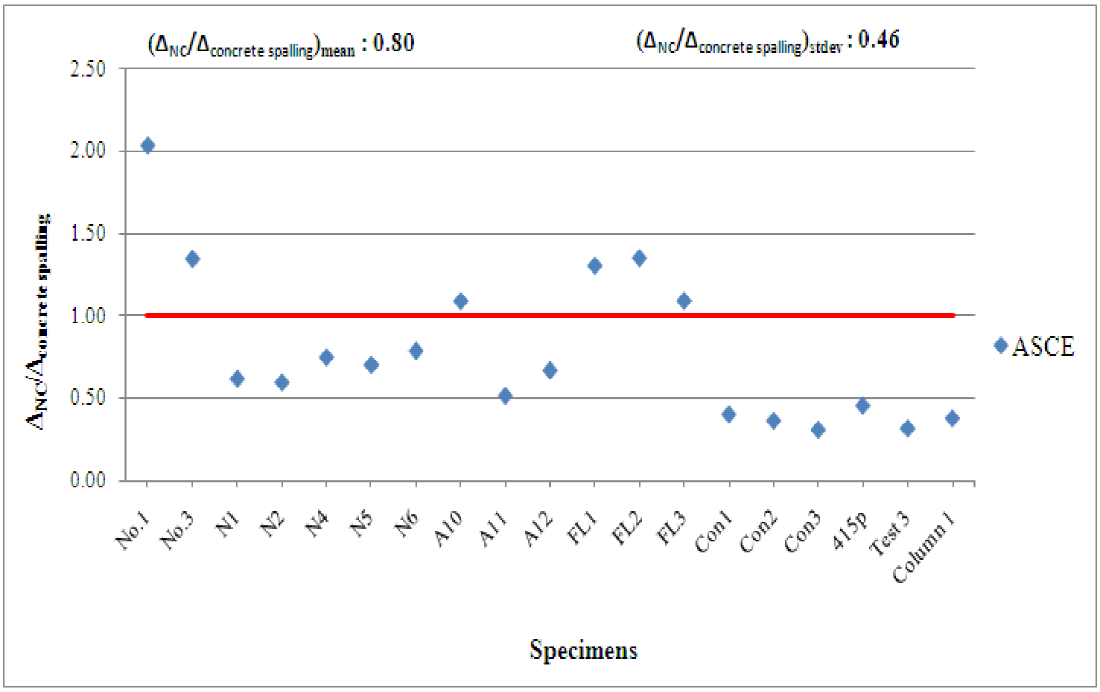

Figure 5.34 : Exceedance ratios of collapsing damage limits according to ASCE for circular columns.

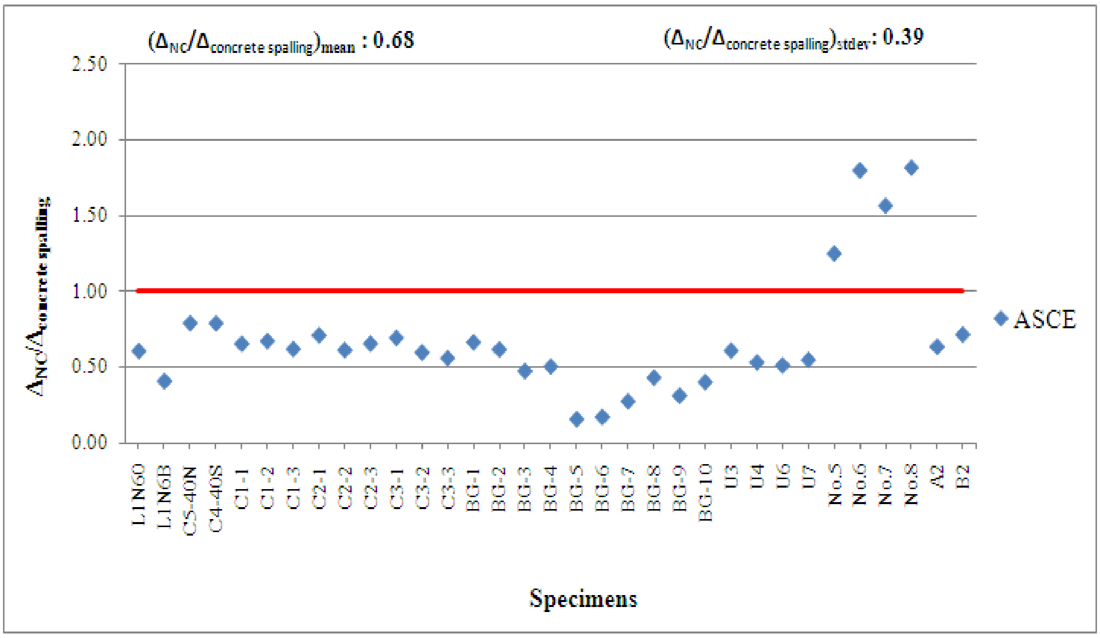

Figure 5.35 : Exceedance ratios of collapsing damage limits according to ASCE for rectangular columns.

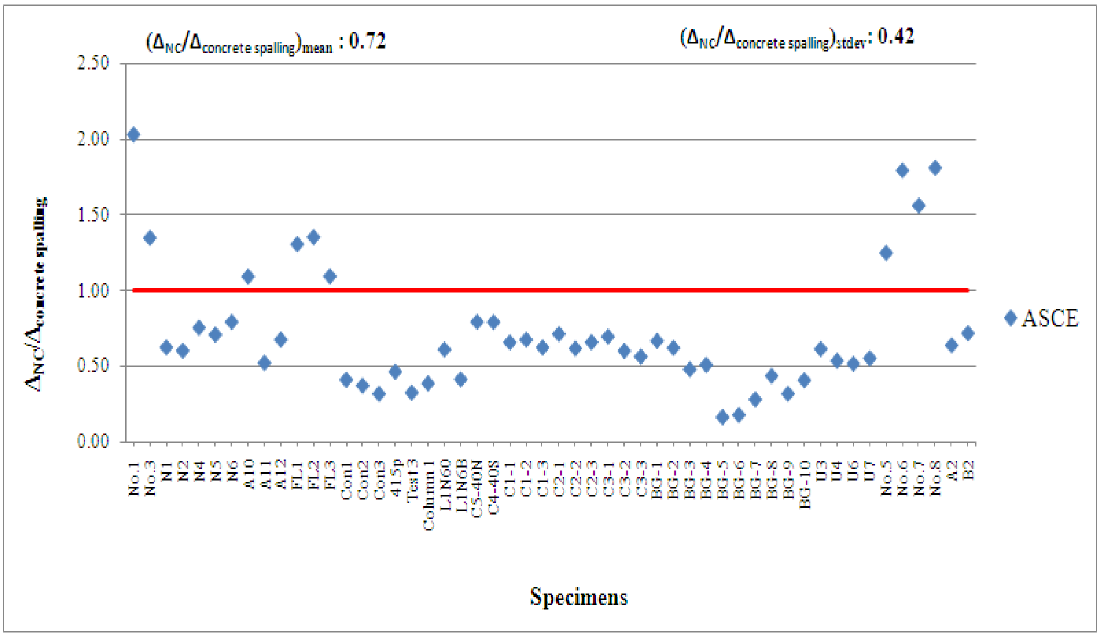

Figure 5.36 : Exceedance ratios of collapsing damage limits according to ASCE for overall.

The exceedance of significant damage limits has been reached to 40% percentage for circular columns apart from No.1 specimen and there is no exceedance point for apart from specimens such as No.5, No.5, No.7 and No.8 for rectangular columns according to ASCE. However, the mean exceedance ratio is 0.72 for overall and the standard deviation of exceedance ratio is 0.42 as given in **Figure 5.34**, **Figure 5.35** and **Figure 5.36**.

According to collapsing damage limits proposed by Turkish Seismic Code, 57% percentage of circular columns and 84% percentage of rectangular columns have been exceeded the collapsing damage limits. The observed damages have not been reached to the collapsing damage limits for 25% percentage of circular and rectangular columns.

According to collapsing damage limits proposed by Eurocode, 21% percentage of circular columns and 63% percentage of rectangular columns have been exceeded the collapsing damage limits. The observed damages have not been reached to the collapsing damage limits for 52% percentage of circular and rectangular columns.

According to collapsing damage limits proposed by ASCE, the observed damages have not been exceeded the collapsing damage limits for almost rectangular columns and 68% percentage of circular columns have been exceeded the collapsing damage limits. The observed damages have not been reached to the collapsing damage limits for 32% percentage of circular columns.

In conclusion;

- TSC, gives the most consistent results for significant damage limits. However, the exceedance of observed damages has been reached to 50% percentage.
- Eurocode, the exceedance ratio is close to 1.00 and also the large exceedance ratio has been seen for some specimens. Therefore, the performance limits proposed by Eurocode shall be discussed for structural members.
- ASCE, is in very safety region according to observed damages for rectangular columns but not so safety for circular columns.

After all these data, TSC is more close to observed damages than Eurocode and ASCE. Eurocode is not exactly safety for structural performance assessments and ASCE is so safety in proposed structural performance limits for rectangular specimens but not so safety for circular columns.

The calculated and observed damages are increasing with reduction axial load ratio of specimens. This ratio is especially distinctive factor for significant and collapsing damages in terms of displacements of specimens.

The span to depth ratio is not effective on observed damages because of the failure type of almost all specimens is flexure failure. The longitudinal reinforcement ratio is not so effective on observed damages. However, the observed damages are increasing with longitudinal reinforcement ratio properly for minimum and collapsing damages.

6. CONCLUSION AND RECOMMENDATIONS

Within the scope of thesis study, ductile concrete columns with different properties are compared in terms of seismic performance assessments by using Turkish Seismic Code 2007, Eurocode 8 and ASCE/SEI 41. The predictions of the methods given in the codes are compared with each other as well as the experimental results. Similarities between the predictions of the methods given in the codes and experimental results and also differences between the codes are displayed by this comparison. Finally, the comparisons show that the performance predictions of the codes may remarkably differ and may significantly contradict with the observed damages.

For minimum damage limit;

- The structural performance limits proposed according to limit section strains of structural materials by Turkish Seismic Code 2007, are corresponding to the observed damages. Therefore, Turkish Seismic Code 2007 gives reliable results for minimum damage limit.
- The structural performance limits proposed according to the chord rotations of structural members by Eurocode 8, are not corresponding to the observed damages and Eurocode 8 gives higher structural performance limits. Therefore, the reliability of Eurocode 8 shall be discussed for minimum damage limit.
- The structural performance limits proposed according to the chord rotations of structural members by ASCE/SEI 41, are not corresponding to the observed damages and ASCE/SEI 41 gives the lower structural performance limits. Therefore, ASCE/SEI 41 is in safety region for minimum damage limit.

For significant damage limit;

- The structural performance limits proposed according to limit section strains of structural materials by Turkish Seismic Code 2007, are corresponding to the observed damages for rectangular columns but not for circular columns. Therefore, Turkish Seismic Code 2007 gives reliable results for rectangular columns but not for circular columns for significant damage limit.

- The structural performance limits proposed according to the chord rotations of structural members by Eurocode 8, are corresponding to the observed damages for rectangular columns but not for circular columns. Eurocode 8 gives higher structural performance limits. Therefore, the reliability of Eurocode 8 shall be discussed for circular columns but Eurocode 8 gives reliable results for rectangular columns because of the acceptable exceedance ratio for significant damage limit.
- The structural performance limits proposed according to the chord rotations of structural members by ASCE/SEI 41, are not corresponding to the observed damages and ASCE/SEI 41 gives the lower structural performance limits. Therefore, ASCE/SEI 41 is in safety region for significant damage limit.

For collapsing damage limit;

- The structural performance limits proposed according to limit section strains of structural materials by Turkish Seismic Code 2007, are corresponding to the observed damages for circular columns but not for rectangular columns. Therefore, Turkish Seismic Code 2007 gives reliable results for circular columns but not for rectangular columns for collapsing damage limit.
- The structural performance limits proposed according to the chord rotations of structural members by Eurocode 8, are corresponding to the observed damages for rectangular columns but not for circular columns. Eurocode 8 gives higher structural performance limits. Therefore, the reliability of Eurocode 8 shall be discussed for circular columns but Eurocode 8 gives reliable results for rectangular columns because of the acceptable exceedance ratio for collapsing damage limit.
- The structural performance limits proposed according to the chord rotations of structural members by ASCE/SEI 41, are not corresponding to the observed damages and ASCE/SEI 41 gives the lower structural performance limits for rectangular columns and circular columns. Therefore, ASCE/SEI 41

is in safety region for rectangular columns and circular columns for collapsing damage limit.

Table 6.1: Comparative mean exceedance ratio table for seismic codes.

Column Type	Minimum Damage			Significant Damage			Collapsing Damage		
	TSC	EC8	ASCE	TSC	EC8	ASCE	TSC	EC8	ASCE
Circular	1.05	1.13	0.45	1.16	1.75	0.91	0.97	1.56	0.80
Rectangular	0.94	1.10	0.47	0.94	1.03	0.80	0.78	0.91	0.68
Overall	0.98	1.11	0.46	1.02	1.30	0.84	0.85	1.14	0.72

Briefly, the predictions of structural performance limits proposed by ASCE/SEI 41 are more safety than Turkish Seismic Code 2007 and Eurocode 8 according to the observed damages. The structural performance limits proposed by Eurocode 8, are not safety for circular columns for three damage limits but only the predicted damage limits are safety for collapsing damage limits. The structural performance limits proposed by Turkish Seismic Code 2007 are safety for rectangular columns for three damage limits but not only safety for circular columns for collapsing damage limit.

In thesis study, it is shown that the observed damages are independent from span to depth ratio. However, the longitudinal reinforcement and especially transverse reinforcement ratio is the most effective factor for observed damages and structural performance limits given by seismic codes. Moreover, the axial load ratio is so effective on observed and proposed damages of specimens.

In conclusion; the obtained results by this study, is valid for 33 rectangular columns and 19 circular columns and the more reliable results can be observed by increasing the numbers of specimens.

Within this scope, the structural performance limits proposed by ASCE/SEI 41, are so safety for three damage limits and so the limit chord rotations for damage levels can be modified.

Eurocode 8 generally is in unsafe region for structural performance limits and so the limit chord rotations cam be modified to get more safety structural performance limits.

The similar studies shall be done to get more reliable structural performance limits proposed by seismic codes. After all, one important recommendation is given below for Turkish Seismic Code 2007.

Especially, the brittle failure of structural members can be evaluated by Eurocode 8 and ASCE/SEI 41 but this evaluation cannot be performed according to Turkish Seismic Code 2007. Moreover, the existing buildings in Turkey have collapsed with brittle failure in recent earthquakes and so this condition becomes very important requirement for Turkish Seismic Code 2007.

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APPENDICES

APPENDIX A.1 : Information of Rectangular Columns

APPENDIX A.1

Table A.1 : Geometric properties of circular columns.

Name	**Diameter (mm)**	**Height (mm)**
No.1	400	800
No.3	400	800
Model N1	250	750
Model N2	250	750
Model N4	250	750
Model N5	250	750
Model N6	250	1500
A10	305	1372
A11	305	1372
A12	305	1372
FL1	457	3656
FL2	457	3656
FL3	457	3656
Con1	152	1140
Con2	152	570
Con3	152	570
415p	609.6	2438.4
Test 3	609.6	3657
Column 1	457.2	2863.9

Table A.2 : Material properties of circular columns.

Name	Concrete Strength	Transverse Steel		Longitudinal Steel	
		Yield Stress	Tensile Strength	Yield Stress	Tensile Strength
	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)
No.1	38	300	-	423	577
No.3	37	300	-	475	625
Model N1	24.1	441	-	446	-
Model N2	23.1	441	-	446	-
Model N4	24.4	441	-	446	-
Model N5	24.3	441	-	446	-
Model N6	23.3	476	-	446	-
A10	27	434	-	448	690
A11	27	434	-	448	690
A12	27	434	-	448	690
FL1	36.6	445	-	477	-
FL2	40	437	-	477	-
FL3	38.6	445	-	477	-
Con1	34.5	620	-	448	-
Con2	34.5	620	-	448	-
Con3	34.5	620	-	448	-
415p	37.2	606.8	-	462	-
Test 3	32.6	351.6	-	315.1	497.8
Column 1	22	379	-	379	-

Table A.3 : Loading information of circular columns.

Name	**Axial Load (kN)**	**P - Δ**
No.1	907	Case - II
No.3	1813	Case - II
Model N1	120	Case - II
Model N2	239	Case - II
Model N4	120	Case - II
Model N5	239	Case - II
Model N6	120	Case - II
A10	200	Case - II
A11	200	Case - II
A12	200	Case - II
FL1	1780	Case - I
FL2	1780	Case - I
FL3	1780	Case - I
Con1	151	Case - I
Con2	151	Case - I
Con3	220	Case - I
415p	1308	Case - III
Test 3	1779	Case - III
Column 1	700	Case - III

Table A.4 : Non-dimensional of circular columns.

Name	**Span-to-Depth Ratio**	**Axial Load Ratio**
No.1	2	0.190
No.3	2	0.390
Model N1	3	0.101
Model N2	3	0.211
Model N4	3	0.100
Model N5	3	0.200
Model N6	6	0.105
A10	4.5	0.101
A11	4.5	0.101
A12	4.5	0.101
FL1	8	0.296
FL2	8	0.271
FL3	8	0.281
Con1	7.5	0.241
Con2	3.75	0.241
Con3	3.75	0.351
415p	4	0.120
Test 3	6	0.187
Column 1	6.26	0.194

Table A.5 : Reinforcement properties of circular columns.

Name	Longitudinal Reinforcement			Transverse Reinforcement			
	Diameter (mm)	Number of Bars	Reinforcement Ratio	Diameter Spiral (mm)	Hoop Spacing (mm)	Cover (mm)	Reinforcement Ratio
No.1	16	20	0.032	10	60	20	1.42
No.3	16	20	0.032	10	60	20	1.42
Model N1	7	25	0.0196	3.1	9	9.9	1.41
Model N2	7	25	0.0196	3.1	9	9.9	1.41
Model N4	7	25	0.0196	3.1	9	9.9	1.41
Model N5	7	25	0.0196	3.1	9	9.9	1.41
Model N6	7	25	0.0196	2.7	14	9.7	0.68
A10	9.5	21	0.0204	4	19	14.5	0.94
A11	9.5	21	0.0204	4	19	14.5	0.94
A12	9.5	21	0.0204	4	19	14.5	0.94
FL1	15.9	30	0.0362	9.5	76	30.2	0.92
FL2	15.9	30	0.0362	6.4	51	30.2	0.60
FL3	15.9	30	0.0362	9.5	76	30.2	0.92
Con1	12.7	8	0.0558	3.7	22	10.2	1.45
Con2	12.7	8	0.0558	3.7	22	10.2	1.45
Con3	12.7	8	0.0558	3.7	22	10.2	1.45
415p	15.9	22	0.0149	6.4	31.8	22.2	0.70
Test 3	19	26	0.0254	6.4	127	20	0.17
Column 1	19	9	0.0156	9.5	305	38.1	0.24

Table A.6 : Geometric properties of rectangular columns.

Name	Cross Section		Height
	Width	Depth	
	b	h	L
	(mm)	(mm)	(mm)
L1N60	600	600	1200
L1N6B	560	560	1200
C5-40N	203	203	610
C5-40S	203	203	610
C1-1	400	400	1400
C1-2	400	400	1400
C1-3	400	400	1400
C2-1	400	400	1400
C2-2	400	400	1400
C2-3	400	400	1400
C3-1	400	400	1400
C3-2	400	400	1400
C3-3	400	400	1400
BG-1	350	350	1645
BG-2	350	350	1645
BG-3	350	350	1645
BG-4	350	350	1645
BG-5	350	350	1645
BG-6	350	350	1645
BG-7	350	350	1645
BG-8	350	350	1645
BG-9	350	350	1645
BG-10	350	350	1645
U3	350	350	1000
U4	350	350	1000
U6	350	350	1000
U7	350	350	1000
No.5	550	550	1650
No.6	550	550	1650
No.7	550	550	1650
No.8	550	550	1650
A2	380	610	2050
B2	380	610	2050

Table A.7 : Material properties of rectangular columns.

Name	Concrete Strength	Transverse Steel		Longitudinal Steel	
		Yield Stress	Tensile Strength	Yield Stress	Tensile Strength
	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)
L1N60	39.20	524.0	673.0	388.0	388.0
L1N6B	32.20	513.7	673.0	388.0	588.0
C5-40N	38.10	514.7	760.2	572.3	729.1
C5-40S	38.10	459.5	761.2	572.3	730.1
C1-1	24.94	459.5	576.5	497	592
C1-2	26.67	459.5	576.5	497	592
C1-3	26.13	459.5	576.5	497	592
C2-1	25.33	459.5	576.5	497	592
C2-2	27.12	459.5	576.5	497	592
C2-3	26.77	459.5	576.5	497	592
C3-1	26.38	459.5	576.5	497	592
C3-2	27.48	459.5	576.5	497	592
C3-3	26.90	459.5	576.5	497	592
BG-1	34.00	570.0	680	445.6	660.0
BG-2	34.00	570.0	680	445.6	660.0
BG-3	34.00	570.0	680	445.6	660.0
BG-4	34.00	570.0	680	445.6	660.0
BG-5	34.00	570.0	680	445.6	660.0
BG-6	34.00	570.0	680	477.8	700.0
BG-7	34.00	580.0	720	455.6	660.0
BG-8	34.00	580.0	720	455.6	660.0
BG-9	34.00	580.0	720	427.8	675.0
BG-10	34.00	570.0	680	427.8	675.0
U3	34.80	470.0	-	430.0	-
U4	32.00	470.0	-	438.0	-
U6	37.30	425.0	-	437.0	-
U7	39.00	425.0	-	437.0	-
No.5	32.00	325.0	429	511.0	675.0
No.6	32.00	325.0	429	511.0	675.0
No.7	32.10	325.0	429	511.0	675.0
No.8	32.10	325.0	429	511.0	675.0
A2	27.60	414.0	-	414.0	-
B2	27.60	414.0	-	414.0	-

Table A.8 : Loading information of rectangular columns.

Name	**Axial Load (kN)**	**P - Δ**
L1N60	8000	Case - II
L1N6B	6000	Case - II
C5-40N	569	Case - II
C5-40S	569	Case - II
C1-1	450	Case - III
C1-2	675	Case - III
C1-3	900	Case - III
C2-1	450	Case - III
C2-2	675	Case - III
C2-3	900	Case - III
C3-1	450	Case - III
C3-2	675	Case - III
C3-3	900	Case - III
BG-1	1782	Case - III
BG-2	1782	Case - III
BG-3	831	Case - III
BG-4	1923	Case - III
BG-5	1923	Case - III
BG-6	1900	Case - III
BG-7	1923	Case - III
BG-8	961	Case - III
BG-9	1923	Case - III
BG-10	1923	Case - III
U3	600	Case - II
U4	600	Case - II
U6	600	Case - II
U7	600	Case - II
No.5	968	Case - II
No.6	968	Case - II
No.7	2913	Case - II
No.8	2913	Case - II
A2	1505	Case - II
B2	1514	Case - II

Table A.9 : Non-dimensional properties of rectangular columns.

Name	**Span-to-Depth Ratio**	**Axial Load Ratio**
L1N60	2.000	0.567
L1N6B	2.143	0.594
C5-40N	3.005	0.362
C5-40S	3.005	0.362
C1-1	3.500	0.113
C1-2	3.500	0.158
C1-3	3.500	0.215
C2-1	3.500	0.111
C2-2	3.500	0.156
C2-3	3.500	0.210
C3-1	3.500	0.107
C3-2	3.500	0.154
C3-3	3.500	0.209
BG-1	4.700	0.428
BG-2	4.700	0.428
BG-3	4.700	0.200
BG-4	4.700	0.462
BG-5	4.700	0.462
BG-6	4.700	0.456
BG-7	4.700	0.462
BG-8	4.700	0.231
BG-9	4.700	0.462
BG-10	4.700	0.462
U3	2.857	0.141
U4	2.857	0.153
U6	2.857	0.131
U7	2.857	0.126
No.5	3.000	0.100
No.6	3.000	0.100
No.7	3.000	0.300
No.8	3.000	0.300
A2	3.361	0.235
B2	3.361	0.237

Table A.10 : Longitudinal reinforcement properties of rectangular columns.

Name	Diameter (mm)	Quantity	Perpendicular to Load		Parallel to Load		Reinforcement Ratio
			Cover (mm)	Number of intermediate bars	Cover (mm)	Number of intermediate bars	
L1N60	25.40	12	44.5	2	44.5	2	0.0169
L1N6B	25.40	12	24.5	2	24.5	2	0.0194
C5-40N	15.90	4	20.7	0	17.7	0	0.0193
C5-40S	15.90	4	20.7	0	20.7	0	0.0193
C1-1	19.05	12	34.0	2	34.0	2	0.0214
C1-2	19.05	12	34.0	2	34.0	2	0.0214
C1-3	19.05	12	34.0	2	34.0	2	0.0214
C2-1	19.05	12	34.0	2	34.0	2	0.0214
C2-2	19.05	12	34.0	2	34.0	2	0.0214
C2-3	19.05	12	34.0	2	34.0	2	0.0214
C3-1	19.05	12	34.0	2	34.0	2	0.0214
C3-2	19.05	12	34.0	2	34.0	2	0.0214
C3-3	19.05	12	34.0	2	34.0	2	0.0214
BG-1	19.50	8	29.0	1	29.0	1	0.0195
BG-2	19.50	8	29.0	1	29.0	1	0.0195
BG-3	19.50	8	29.0	1	29.0	1	0.0195
BG-4	19.50	12	29.0	2	29.0	2	0.0293
BG-5	19.50	12	29.0	2	29.0	2	0.0293
BG-6	29.90	4	29.0	0	29.0	0	0.0229
BG-7	19.50	12	29.0	2	29.0	2	0.0293
BG-8	19.50	12	29.0	2	29.0	2	0.0293
BG-9	16.00	20	29.0	4	29.0	4	0.0328
BG-10	16.00	20	29.0	4	29.0	4	0.0328
U3	25.00	8	22.5	1	22.5	1	0.0321
U4	25.00	8	22.5	1	22.5	1	0.0321
U6	25.00	8	26.1	1	26.1	1	0.0321
U7	25.00	8	26.1	1	26.1	1	0.0321
No.5	20.00	12	40.0	2	40.0	2	0.0125
No.6	20.00	12	40.0	2	40.0	2	0.0125
No.7	20.00	12	40.0	2	40.0	2	0.0125
No.8	20.00	12	40.0	2	40.0	2	0.0125
A2	19.00	18	28.0	2	28.0	5	0.0220
B2	19.00	18	25.0	2	25.0	5	0.0220

Table A.11 : Transverse reinforcement properties of rectangular columns.

Name	Type	Number of Shear Legs	Region of Close Spacing			Region of Wide Spacing		
			Diameter (mm)	Hoop Spacing (mm)	Volumetric Reinforcement Ratio	Diameter (mm)	Hoop Spacing (mm)	Volumetric Reinforcement Ratio
L1N60	RU	4	12.70	100	0.0168	12.70	100	0.0168
L1N6B	RU	4	12.70	100	0.0168	12.70	100	0.0168
C5-40N	R	2	9.50	76.2	0.0148	9.50	76.2	0.0148
C5-40S	R	2	9.50	77.2	0.0144	9.50	77.2	0.0144
C1-1	RJ	4	6.35	50	0.0105	6.35	50	0.0105
C1-2	RJ	4	6.35	50	0.0105	6.35	50	0.0105
C1-3	RJ	4	6.35	50	0.0105	6.35	50	0.0105
C2-1	RI	4	6.35	52	0.0101	6.35	52	0.0101
C2-2	RI	4	6.35	52	0.0101	6.35	52	0.0101
C2-3	RI	4	6.35	52	0.0101	6.35	52	0.0101
C3-1	I	4	6.35	54	0.0097	6.35	54	0.0097
C3-2	I	4	6.35	54	0.0097	6.35	54	0.0097
C3-3	I	4	6.35	54	0.0097	6.35	54	0.0097
BG-1	RI	3	9.53	152	0.0067	9.53	152	0.0067
BG-2	RI	3	9.53	76	0.0134	9.53	76	0.0134
BG-3	RI	3	9.53	76	0.0134	9.53	76	0.0134
BG-4	RI	4	9.53	152	0.0089	9.53	152	0.0089
BG-5	RI	4	9.53	76	0.0178	9.53	76	0.0178
BG-6	RI	4	9.53	76	0.0178	9.53	76	0.0178
BG-7	RI	4	6.60	76	0.0086	6.60	76	0.0086
BG-8	RI	4	6.60	76	0.0086	6.60	76	0.0086
BG-9	RI	4	6.60	76	0.0086	6.60	76	0.0086
BG-10	RI	4	9.53	76	0.0178	9.53	76	0.0178
U3	R	2	10.00	75	0.0104	10.00	75	0.0104
U4	R	2	10.00	50	0.0156	10.00	50	0.0156
U6	RJ	6	6.40	65	0.0144	6.40	65	0.0144
U7	RJ	6	6.40	65	0.0144	6.40	65	0.0144
No.5	RJ	4	12.00	110	0.0128	12.00	220	0.0064
No.6	RU	4	12.00	110	0.0128	12.00	220	0.0064
No.7	RJ	4	12.00	90	0.0156	12.00	180	0.0078
No.8	RU	4	12.00	90	0.0156	12.00	180	0.0078
A2	RJ	4	6.00	110	0.0024	6.00	110	0.0024
B2	RJ	4	10.00	83	0.0091	10.00	83	0.0091

CURRICULUM VITAE

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