SEISMIC PERFORMANCE ASSESSMENT OF WIDE BEAM INFILL JOIST BLOCK FRAME STRUCTURES IN TURKEY

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ABSTRACT

SEISMIC PERFORMANCE ASSESSMENT OF WIDE BEAM INFILL JOIST BLOCK FRAME STRUCTURES IN TURKEY

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Wide-beam frame buildings are prevalent in Turkey since 1980's due to their advantageous characteristics such as ease of construction, construction speed and cost efficiency. However; according to recent experimental studies, wide beam systems demonstrate poor energy dissipation capacity under earthquake. The capacities of the wide-beams may not fully developed at the beam-column joints. The beam reinforcements that do not anchor to the core area of the columns may not reach their full capacities unless special measures are taken. The goal of this thesis is to simulate the behavior of wide beam buildings under earthquake excitation through the earthquake simulation software OpenSees (Open System for Earthquake Simulation). The software occupies Modified Ibarra-Krawinkler Deterioration Model in order to model the hysteresis behavior of interior and exterior wide-beam connections. The hysteresis cycles of several experimental studies are calibrated through a procedure developed based on Haselton's calibration equations. Later this calibration is implemented to the simulation of a wide-beam building model and a vulnerability study is carried out. The deformation limits of Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) are first identified through a pushover analysis. Later, a set of earthquake data is used in consecutive time history analyses and the maximum inter-story drift ratios are recorded for each ground motion input. Finally, a set of fragility curves are produced for different types of ground motion parameters. The results are compared with the results of typical conventional moment frames and flat slab buildings.

Keywords: Wide-beam, OpenSees, Ibarra-Krawinkler hysteresis, time history analysis, fragility curves.

ÖZ

TÜRKİYEDEKİ GENİŞ YASTIK KİRİŞLİ DOLGU ÇERÇEVE SİSTEMLERİNİN SİSMİK PERFORMANS DEĞERLENDİRMESİ

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Yastık kirişli çerçeve binalar (Asmolen çerçeve), inşaat kolaylığı, süresi ve maliyet verimliliği açısından avantajlı olduğundan 1980'lerden sonra Türkiye'de oldukça yaygın hale gelmiştir. Ancak son yapılan araştırmalarda, yastık kirişli sistemlerin deprem altında zayıf enerji sönümleme kapasitelerine sahip olduğu gözlenmektedir. Kolon çekirdeği dışına saplanan kiriş donatılarının yetersiz aderanstan ötürü çekme kapasitelerine ulaşamamaları sebebiyle, yastık kirişler tam kapasitelerine ulaşamayabilmektedir. Bu tez çalışması yastık kirişli binaların OpenSees (Open System for Earthquake Simulation) adlı bir deprem simulasyon yazılımı aracılığıyla, bir deprem hareketi altında davranışını benzeştirmeyi amaçlamaktadır. Bu yazılım ile, Ibarra-Krawınkler Hasar Modeli kullanılarak iç ve dış geniş yastık kirişli kolon bağlantılarının histeretik davranışları modellenmiştir. Bu amaçla, Haselton'un kalibrasyon denklerimlerini kullanan bir prosedür ile bir kaç farklı deneysel çalışmanın histeretik eğrileri kalibre edilmiş ve bu kalibrasyon, geniş yastık kirişli bir bina modeline uygulanarak hasar görebilirlik çalışması yapılmıştır. Statik artımsal itme analizi ile ilk olarak deformasyon limitleri olan; Hemen Kullanım (IO), Can Güvenliği (LS) ve Göçme Önlenmesi (CP) sınır değerleri tanımlanmıştır. Sonrasında, bir deprem veri seti altında zaman tanımlı analizleri gerçekleştirilmiş ve maksimum

göreli kat ötelenme oranları her yer hareketi için kaydedilmiştir. Son aşamada, farklı yer hareketi parametreleri için kırılkanlık eğrileri üretilmiştir. Sonuçlar tipik bir geleneksel kolon kiriş çerçeve bina ve kirişsiz döşeme binalarının sonuçlarıyla karşılaştırılmıştır.

Anahtar kelimeler: Asmolen yastık kirişi, OpenSees, Ibarra-Krawinkler histeresis, zaman tanımlı analiz, kırılganlık eğrileri,

To my Dear Professors

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A	:	Intermediate Parameter in the My Prediction of Panagiotakos and Fardis
a_{sl}	:	Rebar Slip Indicator Variable (0 or 1)
B	:	Intermediate Parameter in the My Prediction of Panagiotakos and Fardis
b_w	:	Width of the Wide Beam Section
c_A	:	Deterioration Exponent
c_C	:	Deterioration Exponent
c_K	:	Deterioration Exponent
c_S	:	Deterioration Exponent
d_{inf}	:	Diagonal Length of the Infill Wall
E_c	:	Elastic Modulus of Concrete
EI_g	:	Gross Stifness
EI_{stf40}	:	Stiffness Crossing at 40% of Yield Stress
E_{inf}	:	Elastic Modulus of the Infill Panel
Es	:	Elastic Modulus of Steel
F_c	:	Strength Cap
f_c'	:	Compressive Stress of Unconfined Concrete
F_i	:	Equivalent Earthquake Load on ith Floor
F_r	:	Residual Strength
F_y	:	Yield Strength
h_{inf}	:	The Height of the Infill Wall
h_w	:	Height of the Wide Beam Section
K_e	:	Elastic Stiffness

K_s	:	Strain Hardening Stiffness
M_{cr}	:	Cracking Torque
M_y	:	Yield Moment
$P(LS/S_a)$	:	Probability of a Response Exceeding a Certain Limit State
PGA	:	Peak Ground Acceleration
PGV	:	Peak Ground Velocity
s^2	:	Square of the Standard Error
S_a	:	Spectral Acceleration
S_d	:	Spectral Displacement
S_v	:	Spectral Velocity
T_1	:	Building'S Natural Period
t_w	:	Infill Panel Thickness
v	:	Axial Load Ratio
V_t	:	Total Equivalent Earthquake Load
W	:	Building Weight
w_{inf}	:	Effective Infill Width
α	:	Ratio of Elastic Moduli
α_c	:	Post Capping Stiffness Ratio
α_s	:	Strain Hardening Ratio
β_C	:	Standard Deviation of the Natural Logarithm of Drift Capacity
$\beta_{D/Sa}$	:	Standard Deviation of the Natural Logarithm of Drift Demand
β_K	:	Stiffness Proportional Damping Factor
β_M	:	The Uncertainty Associated in the Analytical Modelling
δ_1	:	Effective Depth Ratio
δ_c	:	Capping Deformation

δ_i	:	Displacement at ith Floor
Δ_i	:	Interstory Dirft at ith Floor
δ_p	:	Plastic Deformation Capacity
δ_{pc}	:	Post Capping Deformation Capacity
δ_r	:	Deformation at Residual Strength
δ_u	:	Ultimate Deformation Capacity
η_C	:	Median Drift Capacity for a Limit State
$\eta_{D/Sa}$	:	Median Drift Demand Given The Ground Motion Intensity S_a
θ_p	:	Plastic Deformation Capacity
θ_u	:	Ultimate Rotation
κ	:	Residual Strength Ratio
λ_A	:	Accelerated Reloading Stiffness Deterioration Factor
λ_C	:	Unloading Stiffness Deterioration Factor
λ_h	:	Infill Wall Panel-to-Frame Stiffness Parameter
λ_K	:	Basic Strength Deterioration Factor
λ_S	:	Post-Capping Strength Deterioration Factor
ξ_y	:	Neutral Axis Depth at Yield
ρ_{sh}	:	Transverse Reinforcement Ratio
φ_y	:	Yield Curvature

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

Reinforced concrete frames with wide-beam column connections present a poorly developed hysteretic cycle due to the deficient transfer of the bending moment from wide beam to the column, low lateral stiffness and the poor energy dissipation capacity. Therefore, most building codes restricted the use of such structural systems; yet, insufficient amount of research studies resulted in some obscurity in code regulations regarding this issue. For this reason, behavior of wide beam systems needs to be investigated in detail in order to assess the performance of regarded buildings.

Wide beam slab systems with infill blocks were used first in Germany which is not an earthquake prone country. Then, this type of floor system has been commonly used in low-to-moderate seismic regions, such as Australia, France, Spain and Italy. This slab system enables easy and cost-efficient construction of formworks and also provides architectural flexibility. When compared with the other structural components of a building, the floor systems represent the major contributor to the overall cost. However, wide beam floor systems significantly reduce this cost. The ease of formwork construction, maximization of floor to ceiling heights, and the reduced amount of slab reinforcement in the direction perpendicular to the wide beams make this type of structural systems an attractive option. Therefore, their use propagated toward the earthquake prone countries such as the United States and Turkey. Their use is sometimes partially restricted in these countries. Yet, the current Turkish Earthquake Code (2007) allows this type of floor systems with no specific provision. On the other hand, in other regions with high seismicity exists like Japan, New Zealand and Coastal America; use of wide beam systems is highly discouraged.

The application technique for this system varies from one country to another; infill blocks are not used in some applications whereas a lightweight material is placed between the joists in other applications. Its name also varies in different countries. This type of floor is referred to as a banded-floor or slab-band system in the United States and it is named as “asmolen” or ribbed slab in Turkey depending on whether the infill block is employed or not. Typically, the slab system contains a wide, shallow beam which has an outside portion not penetrating through the columns and perpendicular narrow spandrel beams which are usually referred as “joists”. The joists are filled with usually a special type of clay brick or sometimes styrofoam or hollow cinder blocks. (Dönmez, 2013). A typical asmolen structure is shown in Figure 1.1.

Figure 1.1. Wide-beam infill joist block one-way slab (asmolen)

Turkey is one of the countries in which the use of wide-beam slab systems had become quite widespread recently. Its use also expanded toward the high seismicity regions of Turkey. However, when the performance of this type structural system is investigated; a very serious outcome shows up. The field investigations of 2011 Van-Erciş earthquake revealed that the some of the major structural damages in the collapsed buildings arise from premature failure in the form of strong-column weak-beam mode. This construction method leads to premature failure due to insufficient anchorage of wide beam reinforcements and therefore, the wide beam connections do not demonstrate their expected lateral displacement capacities. A photo of an example collapsed building is provided in Figure 1.2.

Figure 1.2. A collapsed Asmolen building in Erciş, 2011 Van Earthquake (Dönmez, 2013)

In the 1998 Adana-Ceyhan Earthquake, it is reported that many wide-beam slab structures collapsed due to existence of weak column members, hanging floors, insufficient reinforcement detailing and poor workmanship (Gulkan, 1998). In 1992 Erzincan Earthquake, most of the buildings with wide-beam slabs either collapsed or exhibited poorer performance than the old RC moment resisting frame buildings in the region (Malley et al. 1993).

Review of the post-earthquake reports shows that the deficiencies in the material and member level of wide-beam frame structures in Turkey were so overwhelming that the failures in earthquakes did not present any distinct behavior of asmolen systems. Therefore, these building were not specifically investigated in the reports and considered as a sub type of RC frame structures. (Dönmez, 2015)

The primary risk posed by wide beam frame structures is that the low lateral stiffness in the buildings due to shallow depth of the beam members results in significant lateral drifts and therefore critical damages in the beam column connections. Furthermore, these structures reach to their maximum strength at higher displacement values which were delayed due to reduced anchorage of the reinforcement bars in the outside portion of the wide beams.

Today, wide beam slab systems are widely adopted in many countries including Turkey. Despite the advantages such as easy and cost efficient construction, architectural flexibility etc., their deficient structural behavior under earthquake poses significant risk likely to cause loss of life and material damage. Further research is necessary to provide a reference study for the future earthquake codes to let them include safer provisions.

1.2. Objective

The main objective of this study is to assess the seismic fragility of a typical wide-beam building with a standard design according to the current version of the Turkish earthquake code. This fragility information is provided in the form of smooth curves that yield the probability of exceeding predefined limit states given a specific level of seismic hazard as a function of a seismic intensity parameter. As a secondary objective, the fragility curve sets as a seismic performance assessment output of the selected wide-beam model building are compared with the fragility curve sets determined in wide beam vulnerability studies in the literature as well as in other vulnerability studies for reinforced concrete moment frames and flat slab buildings.

This study will help to understand the performance of buildings with wide-beam column connections so that a critique can be made regarding the current code provisions that impose certain regulations on use wide-beam systems. Ultimately, the study could serve as a reference research for the future seismic codes.

1.3. Scope

This study consists of an extensive literature review including previous model building applications in OpenSees (Open System for Earthquake Engineering Simulation), applications of Tcl programming language (Tool Command Language) through OpenSees, previous experimental and numerical research studies on wide-beam column connections and also review of the previous calibration studies of the selected deterioration model Modified Ibarra Krawinkler Peak Oriented Hysteresis Model and its implementation to OpenSees. The study also includes 3 phases of numerical simulation of wide-beam systems built through OpenSees. Handling the simulation in phases entails a more accurate approach to characterize the seismic behavior of wide-beam systems. In the last part of the thesis study, a wide beam building with typical geometry and material properties is modelled and a vulnerability study is conducted by producing fragility curves for different ground motion parameters. The results of the vulnerability analysis are compared with the results of reinforced concrete moment frames and flat slab buildings.

First, the wide beam connection hysteretic behavior is simulated through a hysteretic deterioration model. Results of several experimental studies are used in a calibration study to form a generalized procedure that predicts the real hysteretic behavior of both exterior and interior wide-beam column connections. For this purpose, two internal and one external wide-beam column connection experiment setups are modelled in OpenSees and the calibration procedure is applied to all models. Secondly, the connection level simulation is applied to the connections of a two dimensional building frame with typical building properties of prevalent use in Turkey. The connection level characteristic behavior is implemented by assigning the calibrated material models into the spring elements. In the final phase, the selected wide beam frame building is subjected to pushover analysis in order to define its deformation limits of Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). These limits are used in the vulnerability study to predict the probabilities of exceeding a performance level for each ground motion input in a ground motion set after subsequent time history analyses. Fragility curves for different ground motion parameters are ultimately produced for each performance level. In the end, the results of the vulnerability analyses are compared with the results of reinforced concrete moment frames and flat slab buildings which have the similar design features. The phases of this study are summarized in Figure 1.3.

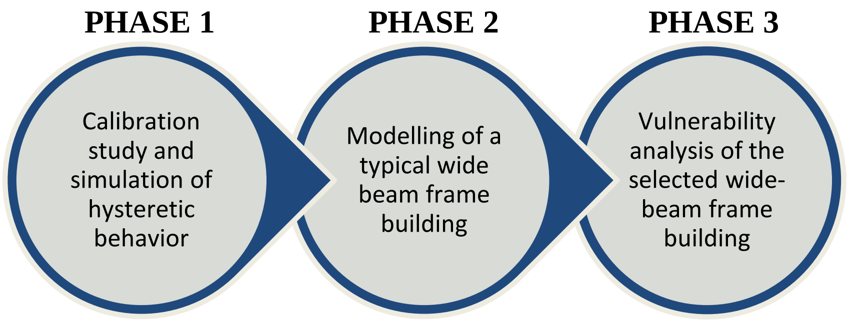

Figure 1.3. Schematic representation of the phases of simulation of the study

1.4. Thesis Organization

This thesis contains a total of five chapters: (1) Introduction, (2) Literature Review, (3) OpenSees Simulation of Wide-beam Systems, (4) Vulnerability Analysis of Real Wide-beam Building (5) Summary, Conclusions and Future Studies. In Chapter 2, the literature studies related to external and internal wide-beam column connections are presented. Within this context, past experimental studies on cyclic behavior of these connections are reviewed. In addition, general information related to computer simulation within OpenSees and applications of the occupied deterioration model into the software are provided. In the next chapter, OpenSees computer models were built for different phases of research. First, a 2D portal frame with wide-beams is subjected to Time History Analysis. However, the sections do not possess the characteristic behavior of wide-beams. Second, experimental hysteresis loops are calibrated and modelled in OpenSees. A generalized calibration procedure is developed and implemented into OpenSees. In chapter four, a wide beam building with typical geometry and material characteristics in Turkish construction practice is modeled as 2D frame with previously calibrated springs. The 2D frame model also includes masonry infill walls modelled as equivalent diagonal struts. Deformation limits are defined with the help of the capacity curve obtained from the pushover analysis. Then, the modelled wide beam building is analyzed under a set of earthquakes and maximum inter-story drifts are recorded for each corresponding earthquake input. Ultimately, a set of vulnerability curves are produced for different earthquake intensities PGA, PGV, Sa, Sv and Sd. In the last part of chapter 4, the performance of the modelled wide-beam building under earthquake demands is evaluated and compared with a conventional reinforced concrete frame buildings as well as the flat slab structures. The last chapter summarizes the whole work presented in the thesis. It includes the summary of the thesis as well as the major findings. The conclusions of the thesis are given in this chapter. Lastly, the chapter concludes with the provisions for the future studies and gives directions to possible future work.

CHAPTER 2

LITERATURE REVIEW ON WIDE-BEAM FRAME SYSTEMS

2.1. Prevalence of Wide-beam Frame Systems

Wide beam slab systems with infill blocks have been used first in Germany which is not an earthquake prone country. A floor system consisting of wide beams with infill blocks has been commonly used in low to moderate seismic regions such as Australia, France, Spain, and Italy. The ease of the formwork construction, maximization of floor to ceiling heights, and the reduced amount of slab reinforcement in the direction perpendicular to the wide beams make this type structural systems an attractive option. This type of floor is referred to as a banded-floor or slab-band system in the US. In regions where high seismicity exist such as Japan, New Zealand and Coastal America, the use of wide beam systems are discouraged.

2.2. Structural Behavior of Wide-beam Frame Systems

Wide beam slabs typically consist of a shallow wide beam in which some of the reinforcement passes outside of the confined column core. Thus, some part of the shear and moment will be transferred through the side face of columns (Gentry and Wight, 1994). The exterior reinforcing bars passing outside of the column core are sometimes unable to transfer the tensile stress to the column under cycling loading due to insufficient bar development which results in the design beam moment capacity falling short. Some level of torque is also generated by these bars onto the transverse and spandrel beams (Benavent-Climent, 2007). A typical wide beam column joint is shown in Figure 2.1.

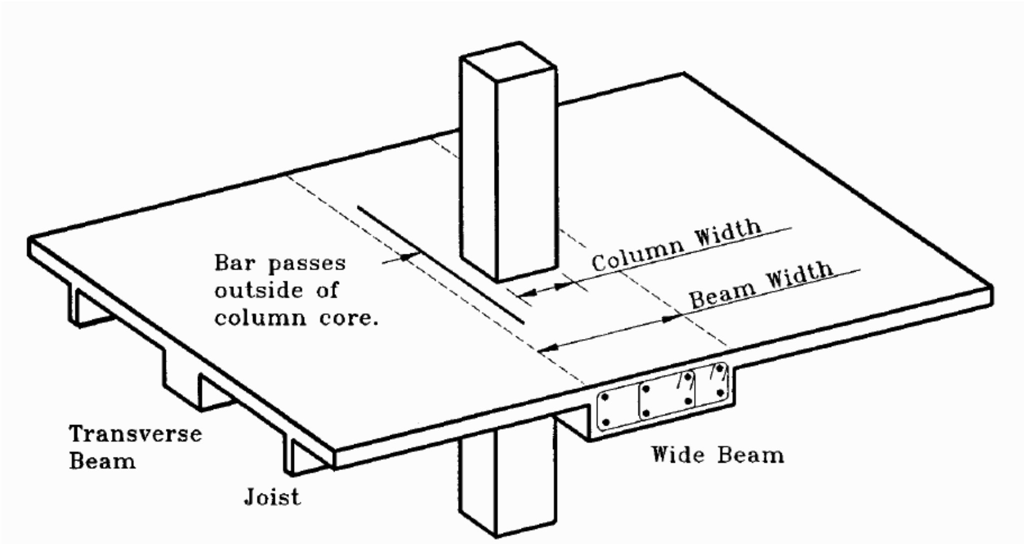

Figure 2.1. A typical wide-beam column joint

Many existing moment resisting frames with wide-beam column connections were designed primarily to resist gravity loads in non-seismic regions where code specifications do not consider earthquake induced loadings. However they present several drawbacks when used in highly seismic regions as a lateral load resisting frame: a deficient transfer of the bending moment from beams to columns; considerably small lateral stiffness and thirdly, poor energy dissipation capacity. (Benavent-Climent et. al., 2009) The reason for having very low lateral stiffness is mainly because the effective depth of wide beam is relatively small and deficient moment transfer is caused by the outer zones of wide beams which also creates considerable amount of torsion at the transverse beams. Therefore, the confinement should be provided delicately to the outside beam portion of the column to improve the torsional rigidity and to provide adequate anchorage for the beam reinforcement bars (Goldsworthy and Abdouka, 2012).

2.3. Code Provisions Regarding Wide-beam Frame Systems

Many earthquake codes around the world have been exposed to modifications due to the development of new construction techniques and changes in designated earthquake demands. American Concrete Institute (1993 ACI-352) disapproved the use of wide beam systems in earthquake prone regions in a committee report. However, in 2002 the same committee allows the use of this type of systems conditionally if certain technical requirements are fulfilled. Similarly in 2011, ACI 318-11 Building Code Requirements for Structural Concrete allows the use of wide beam column frame systems if all longitudinal wide-beam reinforcing steel not passing through the column core is properly confined and if the width of wide beam is not more than 1.5 times the width of the column plus the depth of wide beam. (LaFave and Wight, 2001)

Turkish earthquake codes have been under similar modifications. The earthquake codes started to touch some of the bases of wide beam joist block frame systems after 1967 Adapazari earthquake. Use of this type of systems is prohibited in high seismicity regions of Turkey after the earthquake. Yet, the 1975 Earthquake Code allows use of wide beams as long as structural walls are built. In 1997, obligation on use of structural walls for “Ductile Frames” is lifted. And, the current earthquake code (TEC 2007) has not added any special provisions on use of wide beam systems. According to the current clauses, wide beam depth will not be less than 30 cm and width of the beam should not be more than the column width plus the beam depth. (Dönmez, 2013)

2.4. Past Studies on the Performance of Wide-beam Frame Systems

Many researchers have been studying the wide-column systems for more than two decades. Internal and external connection behavior is investigated through series of experiments. Some studies also included numerical and energy based methods.

2.4.1. Gentry and Wight (1994)

As a result of three consecutive tests on wide-beam column connections, it was concluded that the wide-beam column connections can be used in high seismicity regions if beam width is kept small enough. These connections may even be desirable in certain conditions, since they reduce the rebar congestion in the column core. Yet, the torsional demand on spandrel beams in exterior wide beam connections has to be controlled. In case of interior wide beam connections, bar-slip plays the fundamental role in performance of the connection. Insufficient anchorage may lead to internal bars-slip failures.

2.4.2. LaFave and Wight (2001)

In this study, conventional beam column connections and wide-beam column connections are compared in terms of lateral stiffness, energy dissipation, torsional and shear crack formations. Experiments and analyses are performed to address concerns about earthquake performance of wide-beam column connections. According to the study, both the conventional beam column connection and wide-beam column connection exhibited similar overall load displacement behavior.

2.4.3. Siah et al. (2003)

Two interior reinforced concrete wide beam sub-assemblages and one post-tensioned concrete wide beam sub-assemblage were tested under quasi-static cyclic loading up to a drift ratio of 3.5%. It was found that the wide beam connection is likely to experience severe torsion cracking in the beam portions located at the sides of the column when subjected to severe earthquake loading.

2.4.4. Benavent-Climent (2006)

Existing reinforced concrete moment resisting frames (RCMRFs) with wide-beam column connections which are upgraded with brace type hysteretic dampers are investigated in this research study. Exterior and interior wide-beam column connections with braces are built at 2/3 scale experimental setups. Their collapse behavior under a simulated earthquake excitation is studied using a shaking table. It is observed that the brace dampers reduced the inter-story drifts by 60%-80% and hindered the damage on wide-beams and columns by reducing the maximum rebar strain more than 75%.

2.4.5. Benavent-Climent (2007)

A six story RCMRF prototype structure designed for gravity loads with wide-beam slabs is evaluated experimentally at 2/3 scale model structure. Seismic excitations are applied using a shaking table until collapse. The ultimate energy dissipation capacity and its seismic behavior under a simulated earthquake is observed. Both the exterior and interior beam column joints exhibited poor load displacement response.

2.4.6. Benavent-Climent et al. (2009)

Two test specimens are setup for each sample class representing the exiting interior wide-beam building connections based on the construction practices in 1970s, 1980s and 1990s. The specimens did not reach their expected capacities under cycling loading mainly due to deficient behavior of transverse beams causing severe torsion cracking. The wide beam bars showed very poor bond behavior attributable to small column depth to bar diameter ratio. The reinforcement bars passing outside the column core created significant torsion exceeding the cracking moment M_{cr}.

2.4.7. Benavent-Climent and Zahran (2010)

An energy based approach is developed to investigate the seismic capacity of existing RC wide beam systems in Spain. The procedure consists of converting the frame systems to their equivalent SDOF systems and estimating the ultimate energy input by means of energy balance equations. Seismic capacity assessment is carried out for each of the selected frame systems. Their pushover curves are plotted after static pushover analysis. The earthquake demand curves are intersected with the capacity curves. The vulnerability of the wide beam structures are drawn out.

2.4.8. Li and Kulkarni (2010)

Three full scale exterior wide beam column joints are subjected to experimental and numerical investigations. Their seismic performance investigation is carried out by studying hysteretic response and reinforcement strain profiles. Analytical inspection of the specimens using three dimensional Finite Element Analysis (FE) in DIANA software is also validated with the experimental results. A bond slip model is also occupied in the analyses. The study showed that wide beam-column joints, when designed with suitable parameters, perform quite well in carrying the horizontal lateral loads. However, the torsional behavior of transverse beams dominates the seismic performance of wide beam-column joint specimens and therefore, the design and detailing of the transverse beam is a critical issue which needs to be carefully addressed.

2.4.9. Goldsworthy and Abdouka (2012)

Two half scale subassemblies representing exterior wide-beam column connections of four story frames are tested. The first specimen was detailed in accordance with the current construction practice in Australia. In the second specimen, some simple modifications were made: top and bottom beam longitudinal bars closer to the column and anchoring the bottom longitudinal bars properly using 90 degree stirrups. The variation in detailing between the two specimens would result in a slight increase in cost and no change in the detailing practice. However, it contributes significantly to the earthquake performance of the connections by increasing both the load and displacement capacity.

2.4.10. Dönmez (2013)

The current Turkish earthquake code does not have any special provisions for the design of wide beam systems except the minimum beam depth and maximum width. In this perspective, a set of 7 existing buildings designed in accordance with TEC 2007 are evaluated and their fundamental periods and the mode shapes are found. Their lateral displacements are calculated in the allowed limits by TEC 2007. However, their earthquake performance yielded conflicting results that indicate wide beam systems not developing its full capacity. Therefore, it is feasible to take measures that reduce the lateral drift in wide beam buildings until an extensive research is carried out and the required design criteria are specified by the earthquake code.

2.4.11. Fateh, A., Hejazi, F., Zabihi, A. and Behnia, A. (2013)

A full scale RC wide beam column joint is experimented under concentrated gravity loading. The loading continued until a failure in one of the members is observed. The joint behavior is evaluated for different orientation wide-beam longitudinal reinforcement, spandrel reinforcement and existence of the shear link. The results demonstrated that the wide beams which have longitudinal reinforcement concentrated in the joint region foster 24% higher ultimate capacity.

2.4.12. López-Almansa et al. (2013)

Short to mid-height RC buildings with one way wide-beam slabs have several concerned behavior including deficient stiffness in the transverse direction where only spandrel beams and joists work. Three levels of analyses are held for selected 3 and 6-story buildings; code type analysis, pushover analysis and time history analysis. Their vulnerability analyses showed that these buildings exhibited inadequate seismic behavior for the target drift at collapse prevention (CP).

2.4.13. Dönmez (2015)

The current practice of use wide-of beam infill joist block frames is evaluated for TEC 2007 regulations. An example structure of 6-story building designed under TEC 2007 provisions is evaluated for earthquake performance. The code defined lateral load analysis is performed using the ETABS software. The system has insufficient performance under both the displacement demand calculated by the code definition of the drift demand and by the method developed by Lepage (1996). The research puts out the necessity of further attention for the design of wide-beam systems in Turkish Earthquake Code (2007).

CHAPTER 3

OPENSEES SIMULATION OF WIDE-BEAM CONNECTIONS

3.1. General

In this section, several past experimental research studies of the wide-beam connections are carefully reviewed and their experimental setups are simulated in OpenSees. The OpenSees models are composed of four rotational springs defined at the ends of beam column members in the joint. All the geometric, material and loading characteristics of the experiment setups are assigned to the models.

In the second part of this chapter; an extensive calibration study is conducted. A generalized calibration procedure that can be applied to any wide-beam connection is developed by slightly modifying the calibration procedure of Haselton et. al. (2008). Through this calibration the seismic behavior of wide-beam column connections is simulated in a realistic manner.

3.2. Open System for Earthquake Engineering Simulation (OpenSees)

Open System for Earthquake Engineering Simulation (OpenSees) is an object oriented framework for building models of structural and geotechnical systems, performing nonlinear analysis with the model and processing the response results. To conduct model creation and analysis the scripting language Tcl/Tk has been extended to incorporate features of OpenSees. Tcl/Tk language has many features for dealing with variables, expressions, loops, data structures that are quite useful for performing the simulation. OpenSees software is developed by Pacific Earthquake Engineering Research Center at the University of California, Berkeley.

3.2.1. OpenSees Framework

To date, a large number of researchers have contributed to this framework with the software components that enable researchers and practicing engineers to accomplish sophisticated simulations of the earthquake response of structures. These components include model-building tools, model domain definitions, element formulations, material models, analysis procedures, numerical solvers, data management tools, and methods to support reliability analysis. These components are integrated into different classes. OpenSees classes can be classified into three categories: (1) domain classes, which encapsulate domain component objects (e.g., element, node, load pattern, and single and/or multipoint constraint objects); (2) analysis classes, which include classes responsible for performing a fundamental operation for analysis (e.g., solution algorithm, equation solver, integrator); and (3) model builder classes, which populate the domain classes based on user input (McKenna et al. 2010). Introduction of new modules into OpenSees requires implementation of classes in all three aforementioned categories. OpenSees class structure is shown in Figure 3.1.

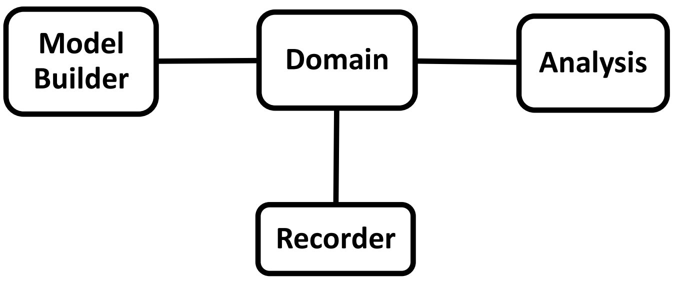

Figure 3.1. Class structure of OpenSees

3.2.2. Model Builder Class

Model Builder class constructs the objects in the model and adds them to the domain. This class includes a set of objects. Hence, the body is divided into elements and nodes. The user defines constraints and loads acting on the elements and nodes. The following objects are available in the Model Builder class:

- Node
- Mass
- Material
- Section
- Element
- LoadPattern
- TimeSeries
- Transformation
- Block
- Constraint

3.2.3. Domain Class

Holds the state of the model at time t_i and is responsible for storing the objects created by the Model Builder and for providing the Analysis and Recorder objects access to Model Builder objects. Domain objects are shown in Figure 3.2.

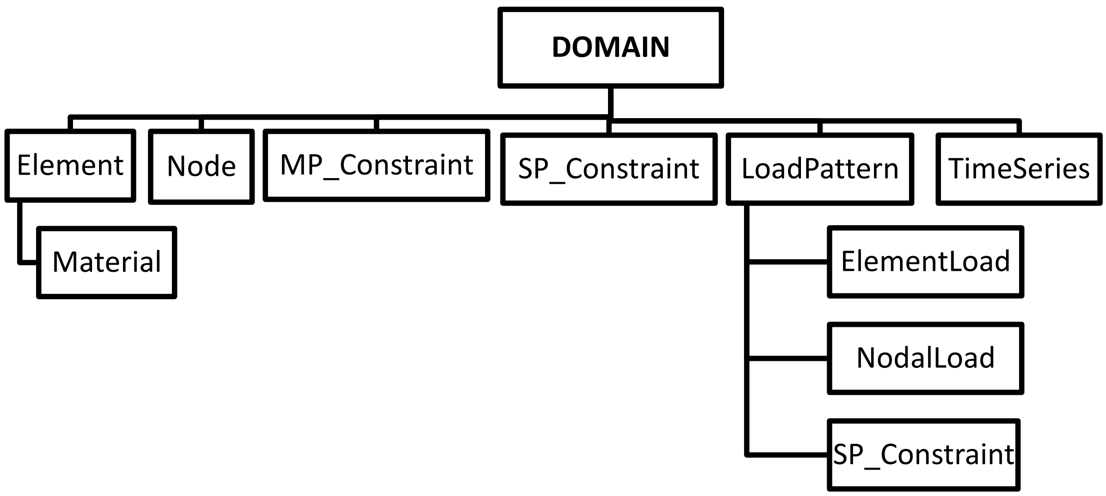

Figure 3.2. Class Objects Structure of Domain

3.2.4. Analysis Class

Moves the model from the state at time t_i to the state at time t_i+dt. Analysis objects are shown in Figure 3.3.

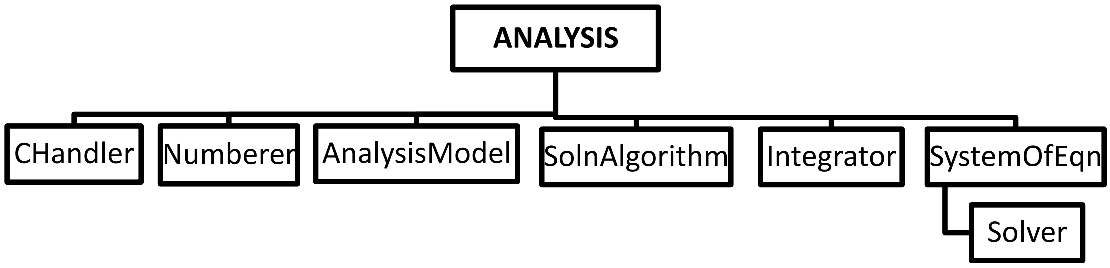

Figure 3.3. Class Objects Structure of Analysis

3.3. Ibarra-Medina-Krawinkler Deterioration Model

Seismic analysis and design require careful investigation of the hysteretic behavior of structures. Hysteresis is a highly nonlinear phenomenon stemming from the inelastic material behavior, energy dissipation and interface friction under a strong earthquake excitation. Availability of constitutive hysteresis models helps to consider the deterioration characteristics in the hysteresis behavior during design or analysis of a structure. Several models have been developed and are widely used such as Clough's model (Clough 1966), Takeda's model (Takeda et al. 1970), the Bouc-Wen model (Bouc and Wen, 1976) and Ibarra-Medina-Krawinkler model (Ibarra et al., 2005).

Ibarra-Medina-Krawinkler model is composed of a trilinear monotonic backbone curve providing significant versatility for different deterioration modes. The model includes post-capping softening branch, residual strength and cyclic deterioration. Negative stiffness branch of post-peak response enables modelling of strain-softening behavior associated with concrete crushing, bond slip failure and rebar buckling. The model also incorporates peak-oriented cyclic response which enables additional modes for cyclic deteriorations.

3.3.1. OpenSees Implementation of the Deterioration Model

Lignos (2008) implemented the hysteretic deterioration model into OpenSees for both peak-oriented hysteretic response and pinched hysteretic response. The sole difference between the deterioration models is how they handle the reloading branch. The backbone curve is presented in Figure 3.1. Initially, loading proceeds along an elastic stiffness K_e until the yield moment M_y is reached. Beyond the yield point, the loading follows a linear post yield behavior with a strain hardening stiffness K_s until it reaches a capping the point. The interval from the yield point to the capping point is named as the plastic rotation θ_p. After the component exhausts its plastic rotation capacity, a post capping rotation is observed. In this region, strength deteriorates along a negative stiffness path until a residual strength F_r is achieved. Then, it remains constant until the component reaches ultimate rotation θ_u.

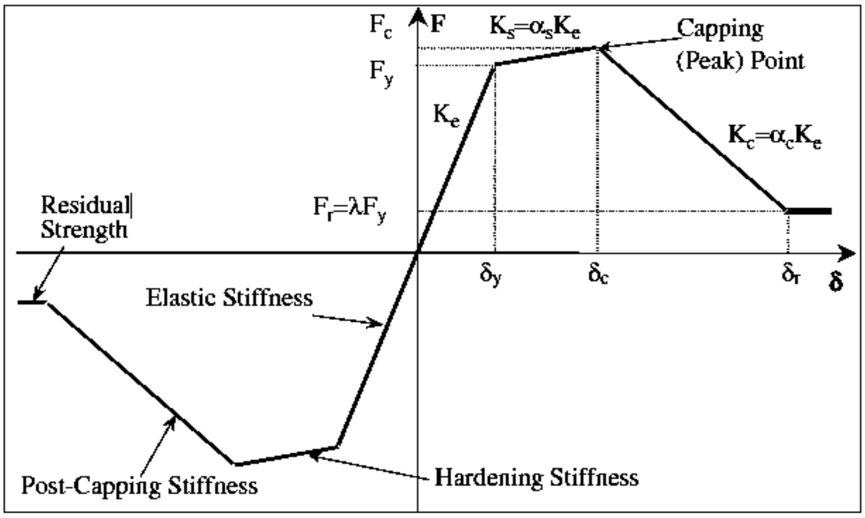

Figure 3.4. Ibarra-Medina Krawinkler Deterioration Model Backbone Curve (Ibarra et. al., 2005)

The deterioration model requires specification of at least seven parameters. These parameters are calibrated using the experimental data. Modified Ibarra-Medina-Krawinkler Deterioration Model with Peak-Oriented Hysteretic Response material (ModIMKPeakOriented) is an already defined material function within OpenSees.

The function requires the following input parameters which later are derived in this report by calibrating to the available hysteresis loops from experiments:

δ_c = Capping deformation (deformation associated with F_c for monotonic loading)

F_y = Effective yield strength, incorporating "average" strain hardening

δ_y = Effective yield deformation (= F_y/K_e)

K_e= Effective elastic stiffness

F_r = Residual strength capacity

δ_r = Deformation at residual strength

δ_u = Ultimate deformation capacity

δ_p = Plastic deformation capacity associated with monotonic loading

δ_{pc}= Post-capping deformation capacity associated with monotonic loading

F_c/F_y = Post-yield strength ratio

κ = Residual strength ratio = F_r/F_y

α_s = Strain hardening ratio = $K_s/K_e = \frac{[(F_c/F_y)/\delta_p]}{K_e}$

α_c = Post-capping stiffness ratio = $K_{pc}/K_e = \frac{(Fc/\delta pc)}{K_e}$

F_c = Strength cap (maximum strength, incorporating "average" strain hardening)

In this study, the peak-oriented hysteretic response is selected to simulate the hysteretic behavior of wide beam connections. Zero length element plastic hinges are assigned at the both ends of each component in the simulation model. While the zero length hinges are plastic, the beam and column elements are generated with elastic material function in OpenSees. The material model function considers following deterioration modes of the cyclic response:

- **Basic strength deterioration:**

Degradation of the yield strength for each loading cycle is reflected in the deterioration model. The strain hardening slope also deteriorates inclining toward right in the hysteresis cycles.

- **Post capping strength deterioration:**

The degradation of softening branch occurs in each hysteresis cycle by moving toward the origin.

- **Unloading stiffness deterioration:**

The degradation of the unloading stiffness occurs by abating its stiffness in each hysteresis cycle.

- **Accelerated reloading stiffness deterioration:**

This deterioration mode is only valid in pinched hysteresis and peak-oriented hysteresis models and is excluded in bilinear Ibarra-Krawinkler hysteretic model. The stiffness slope of reloading branch is decreased in each hysteresis cycle.

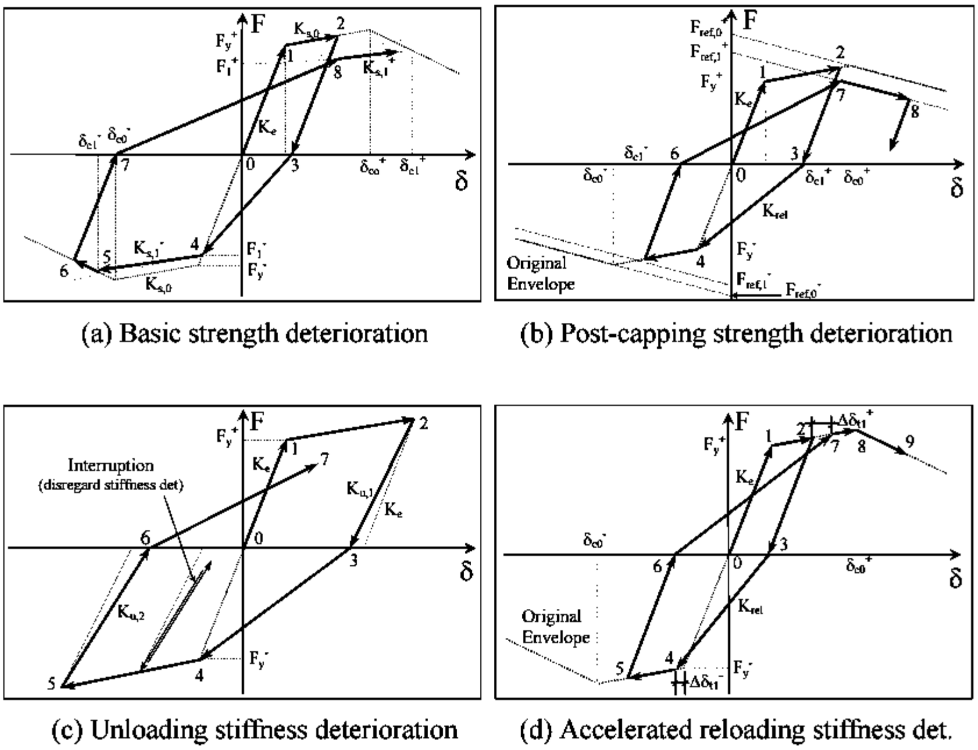

Figure 3.5. Individual deterioration modes of Ibarra-Medina Krawinkler Peak Oriented Deterioration Model (Ibarra et. al., 2005)

3.3.2. Calibration of the Deterioration Model

Ibarra and Krawinkler (2005) had originally proposed a calibration of the parameters of their model for steel, wood and reinforced concrete (RC) specimens using the original hysteresis rules. Yet, subsequent studies provided more extensive research providing better and easier calibration for the Modified Ibarra-Krawinkler Deterioration Model. Haselton et al. (2008) proposed a calibration procedure based on 255 tests of RC columns and developed a set of formulae that can be used to calculate the necessary parameters in order to develop the full backbone curve and establish a rate of hysteretic degradation knowing just a few of the material and geometrical characteristics of a reinforced concrete column. Haselton et al. (2008) derived both simplified and more complex equations for estimation of the model parameters. The calibration procedure is slightly modified in order to reach a more implicit procedure which includes no visual calibration step.

- **Step 1: Prediction of Yield Moments (M_y^+ and M_y^-):**

These parameters are calibrated either graphically or analytically. In the original paper of the deterioration model, it is advised to calibrate yield moments graphically. On the other hand, some research papers on wide-beam column connection occupied stress-block approach or a concrete model to predict yield moment values. Haselton used flexural strength predictions of Panagiotakos and Fardis (2001) in his calibrations. He declares that the method works very well and matches with the graphically calibrated values. Alternatively, Whitney stress block approach also yields good prediction for yield moment M_y in Modified Ibarra-Krawinkler Deterioration Model. However, his approach is made for conventional beam column specimens and his prediction can be an overestimate for wide beams, since premature yielding may be observed in case the member is poorly confined for bar-slip. Therefore a correction multiplier is employed in the prediction.

The prediction of Panagiotakos and Fardis (2001) is used in our calibration study. The following equations are implemented into the model source code.

$$\frac{M_y}{bd^3} = \varphi_y \left\{ E_C \frac{\xi_y^2}{2} \left(\frac{1+\delta_1}{2} - \frac{\xi_y}{3} \right) + E_S \frac{(1-\delta_1)}{2} \begin{bmatrix} \rho_1(1-\xi_y) + \rho_2(\xi_y - \delta_1) + \\ \frac{\rho_v}{6}(1-\delta_1) \end{bmatrix} \right\}$$

(3.1)

Where;

- The yield curvature, $\varphi_y \approx 1.8 f_C / E_C \xi_y d$
- Neutral axis depth at yield, $\xi_y = \sqrt{(\alpha^2 A^2 + 2\alpha B)} - \alpha A$
- Ratio of elastic moduli, $\alpha = E_S / E_C$
- The intermediate parameter, $A = \rho_1 + \rho_2 + \rho_v + N/bdf_y$
- The intermediate parameter, $B = \rho_1 + \rho_2\delta_1 + \rho_v(1+\delta_1)/2 + N/bdf_y$
- Effective depth ratio, $\delta_1 = d_{eff}/d$

- **Step 2: Prediction of Initial Stiffness (K_e):**

Initial stiffness is estimated numerically using conventional beam column prediction equations in the past studies of wide-beam column joints. Benevant Climant used St. Venant's theory (ACI, 2010) for initial stiffness K_e. Similarly, Sugono's method (1968) which defines an empirical factor for the moment-chord rotation of beams and columns is also widely adopted. Initial stiffness is calibrated using the experimental output in the original paper of Ibarra (2005). However, it is seen as necessary to build an estimation rule for the general behavior. Haselton's K_e prediction equation is employed and a correction multiplier is employed to calibrate with the experimental outputs.

$$\frac{EI_{stf40}}{EI_g} = 0.17 + 1.61 \left[\frac{P}{A_g f_c'} \right], where\ 0.35 \leq \frac{EI_{stf40}}{EI_g} \leq 0.8$$

(3.2)

- **Step 3: Prediction of Plastic Rotation Capacity (θ_p):**

The total rotation from the yield point to the capping point is defined as the plastic rotation capacity in Ibarra-Krawinkler Deterioration Model. In referenced studies this parameter is usually replaced by the ductility ratio (μ). Benevant Climant (2007) finds the ductility ratio parameter to be 9 for beam elements and 13 for column elements. Haselton's prediction equation gives consistent estimation for the plastic rotation capacity. The plastic rotation capacity θ_p is calculated using the below equation:

$$\theta_p = 0.13(1 + 0.55a_{sl})(0.13)^V(0.02 + 40\rho_{sh})^{0.65}(0.57)^{0.01f'_c} \quad (3.3)$$

Where;

a_{sl}: Rebar slip indicator variable (0 or 1)

v: Axial load ratio $= P/A_g f'_c$

ρ_{sh}: Transverse reinforcement ratio

f'_c: Compressive stress of unconfined concrete

- **Prediction of Post Capping Rotation Capacity (θ_{pc}):**

This parameter is defined as the total rotation from the capping point to the point where the negative stiffness line intersects the rotation axis. Post capping behavior is not defined in other numerical studies on wide-beams. Haselton's prediction equation is again used to predict this parameter

$$\theta_{pc} = 0.76(0.031)^V(0.02 + 40\rho_{sh})^{1.02} \leq 0.1 \quad (3.4)$$

- **Prediction Strain Hardening Ratios (a_s^+ and a_s^-):**

This parameter defines the slope of post yield behavior. The parameter has almost intolerent effect on the calibration.

- **Prediction of Deterioration Parameters and Exponents (λ_A, λ_K, λ_S, λ_C, c_A, c_K, c_S, c_C):**

Modified Ibarra Krawinkler Hysteresis Model employs 4 different deterioration modes including Basic Strength Deterioration, Unloading Stiffness Deterioration, Accelerated Reloading Stiffness Deterioration and Post-Capping Strength Deterioration and 4 different exponents for each corresponding deterioration mode. These parameters are not estimated through a prediction formula. They are calibrated by matching with an experimental hysteresis. The cyclic deterioration parameters λ_A, λ_K, λ_S and λ_C have also exponents of c_A, c_K, c_S and c_C which lift the effectiveness of the cyclic deterioration parameters. Since the cyclic deterioration parameters are not sensitive to small changes, interval values are determined for different deterioration levels. Above 10.0 is accepted as no deterioration, 2 – 9 is moderate deterioration, and 1 is full deterioration. Acceptable values are sought in this report for all types of wide-beam column connections.

Benavant-Climant (2007) had used a single strength deterioration parameter of α = 2.0 for both wide-beam and column elements.

- **Prediction of Post Yielding Hardening Stiffness (M_c/M_y):**

Post yielding hardening stiffness is also estimated through the calibration equation. It is the indication of residual strength ratio.

$$\frac{M_c}{M_y} = 1.25(0.89)^{V}(0.91)^{0.01f_c'} \tag{3.5}$$

3.4. Modelling of Wide-beam Column Connections of the Experiments

A calibration study is carried out for different wide-beam column connections which are investigated in previous experimental studies. A general procedure is developed to reflect the connection behavior through calibration equations. The selected studies for the calibration of the wide beam connection behavior involves two interior wide beam connections experimented by Benavent Climent et. al. (2010) and one exterior connection by Li and Kulkarni (2010).

3.4.1. Benavent-Climent (2010) Specimen IL and IU

Benavent-Climent et. al. (2010) built an experiment set up for two selected connections of a prototype structure designated as IU and IL. The ends of the wide beams are pin supported by a vertical link. While it stops vertical displacement, free horizontal movement is allowed. The column was pin supported at the base and pushed laterally by hydraulic actuator. 40kN point gravity loads are applied on the beams at a distance of 900mm from the column axis. Also, an axial load of P is applied to both test setups. Whereas the value of P is equal to 200kN for specimen IL, it is 75kN for specimen IU in order to keep the axial load ratio v = 0.1.

$$v = \frac{P}{h_c b_c f_c'} \tag{3.6}$$

The cyclic loading is performed by means of an actuator which provides displacements in the following pattern: 0.5Δy, 0.75Δy, 1.0Δy, 2Δy, 3Δy, 4Δy and so on. Δy is defined as the predicted yield displacement (by Sugano, 1968) which was calculated as 59mm for IL and 34mm for UL. Maximum bending moments applied to the columns (58kNm in IL and 29 kNm in IU) and to the beams (68.8 kNm in IL and 38.9 kNm in IU). The experimental set-ups for specimens IL and UL are shown in Figure 3.6 and Figure 3.7.

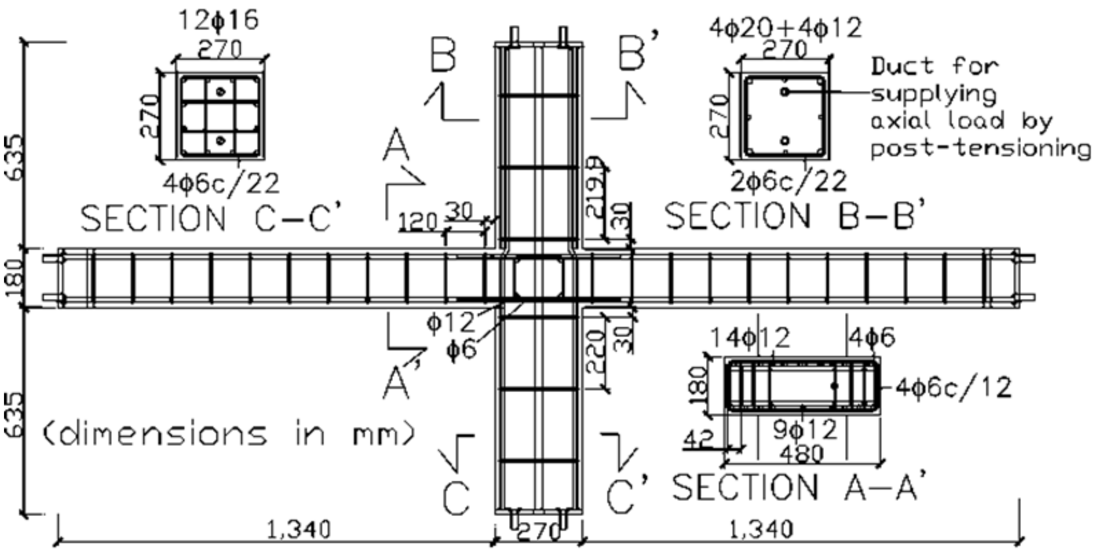

Figure 3.6. Geometry and reinforcing details of the wide beam column connection specimen IL (Benavent-Climent et. al. 2010)

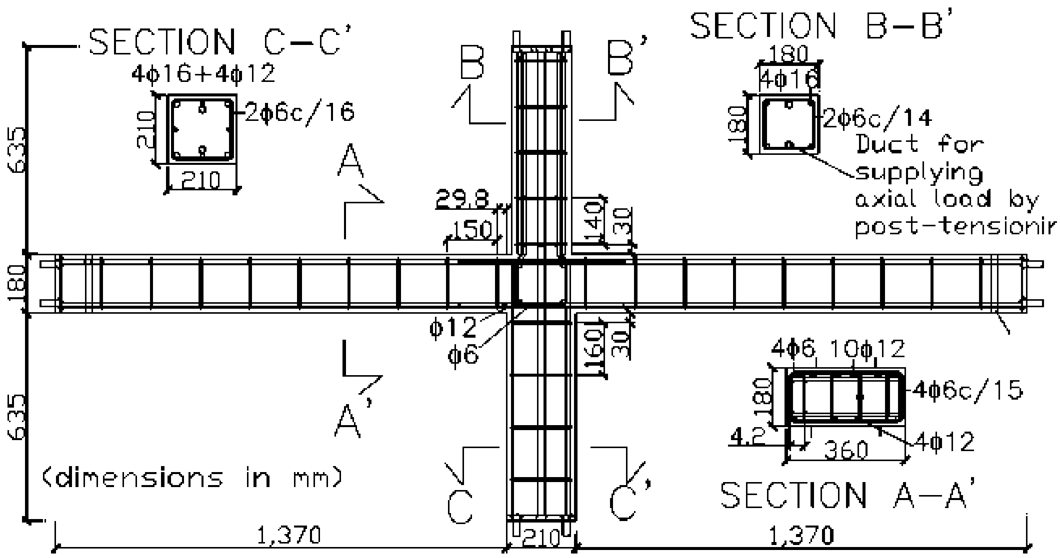

Figure 3.7. Geometry and reinforcing details of the wide beam column connection specimen UL (Benavent-Climent et. al. 2010)

The specimen IL has the beam dimensions of 480x180mm and column dimensions of 270x270mm; and the specimen IU has the beam dimensions of 360x180mm and column dimensions of 210x210mm. The transverse shear reinforcements vary for the specimens. Wide-beam in the specimen IL has 4Ø6c/12 (4 closed, 6mm stirrups with 12cm spacing along the member) with, IL column has 4Ø6c/22, IU wide-beam has 4Ø6c/15, and IU column has 2Ø6c/14 as the shear reinforcement. The transverse reinforcement ratios are calculated as in below.

$$\rho_{sh} = \frac{A_{sh}}{s.b} \tag{3.7}$$

Where;

A_{sh}: Shear reinforcement area
s: Reinforcement spacing
b: Beam width

The axial load is directly applied to the columns by means of post tensioned rods. The average cylindrical compressive strength of concrete is tested to be 24.9 MPa. In addition to the parameters estimated by the above equations, some initial geometry and material input parameters are also gathered from the selected experimental study in Table 3.1.

Table 3.1. Material and geometry parameters gathered from the experimental study

Material and Geometry Parameters									
Spec.	Member	A_{sh} (mm²)	s (mm)	P (kN)	A_g (m²)	f_c' (Mpa)	v	a_{sl}	ρ_{sh}
IL	Column	113.1	220	240	0.0729	24.9	0.132	1	0.0019
	Beam	113.1	120	5	0.0864	24.9	0.002	1	0.0020
UL	Column	56.6	160	115	0.0441	24.9	0.105	1	0.0017
	Beam	113.1	150	5	0.0648	24.9	0.003	1	0.0021

3.4.1.1.OpenSees Model

Model Geometry: The model geometry is composed of 5 element nodes and 4 spring nodes. The spring nodes are constrained in translational degrees of freedom to the element nodes through equalDOF command. The model geometry can be inspected in Figure 3.8.

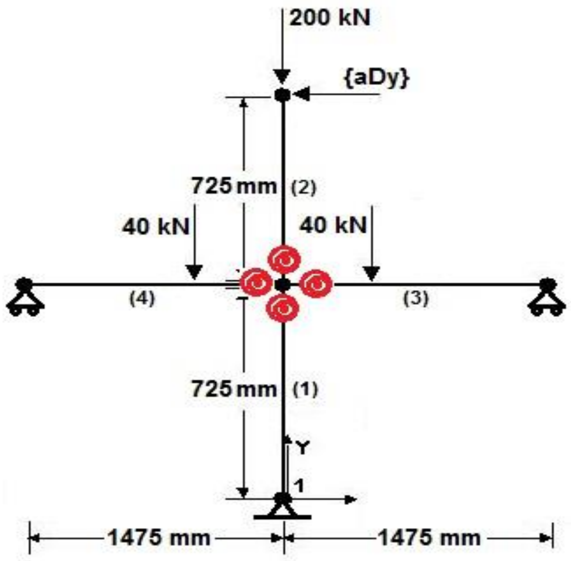

Figure 3.8. Model geometry of the specimens

Material Properties: The system nonlinearity is assigned to the zero-length springs using Ibarra-Krawinkler peak oriented uniaxial material and the beam column elements are modeled as linear elastic elements. The Ibarra-Krawinkler material parameters are obtained using Haselton's calibration equations given in Section 3.3.2. Some input parameters are directly obtained from Benavent-Climent's experiment results. Yet some parameters required further calibration. The calibration process is presented in the next sections. The member stiffness values for linear beam-column elements are calculated using the equation defined in ACI (American Concrete Institution) code.

$$E_c = 4750\sqrt{f_c'} \cong 23700\ MPa \tag{3.8}$$

Element Definition: The simulated interior wide-beam column joint system is modelled with elastic beam-column elements connected by zero length elements which serve as rotational springs to represent the structure's nonlinear behavior. The springs follow a peak oriented bilinear response based on the modified Ibarra Krawinkler Deterioration Model.

Recorder Objects: Recorder objects are used to monitor what is happening during the analysis and generate output for the user. The hysteresis loop is formed using this recorded data. As in the experiment, top displacement and the applied force are monitored. The recorder objects monitors the nodal displacement of node 3 (top displacement) and the reaction force of the column element 2 (end of upper column).

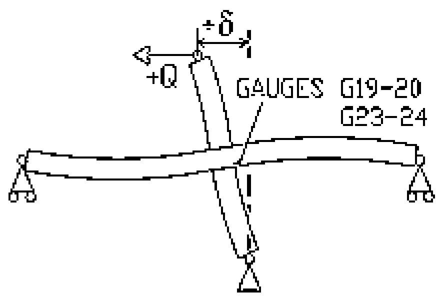

Figure 3.9. Monitored displacement location of the specimen IL

Analysis Object: A set of analysis commands are used to define analysis objects. First, "constraint Plain" command is used to define how the analysis handles boundary conditions. Numberer RCM is used for band-width optimization. The tolerance limit is then defined for convergence test. A tolerance value of 1.0e-6 with maximum 400 iterations is accepted as convergence criteria. Newton Algorithm command which updates tangent stiffness at every iteration is employed. This command is used to construct a NewtonRaphson algorithm object which uses the Newton-Raphson method to advance to the next time step. Since, a displacement controlled analysis will be carried out, Displacement Controlled Integrator is defined.

Gravity Analysis: Gravity analysis is handled prior to a cyclic analysis, since the column behavior changes drastically with the applied axial load. An axial load of 200 kN is applied to top end of upper column for the specimen IL and 75 kN for the specimen UL. Also, 40 kN point loads are placed on beams at 900 mm away from the joint. The loading is displayed schematically in Figure 3.10.

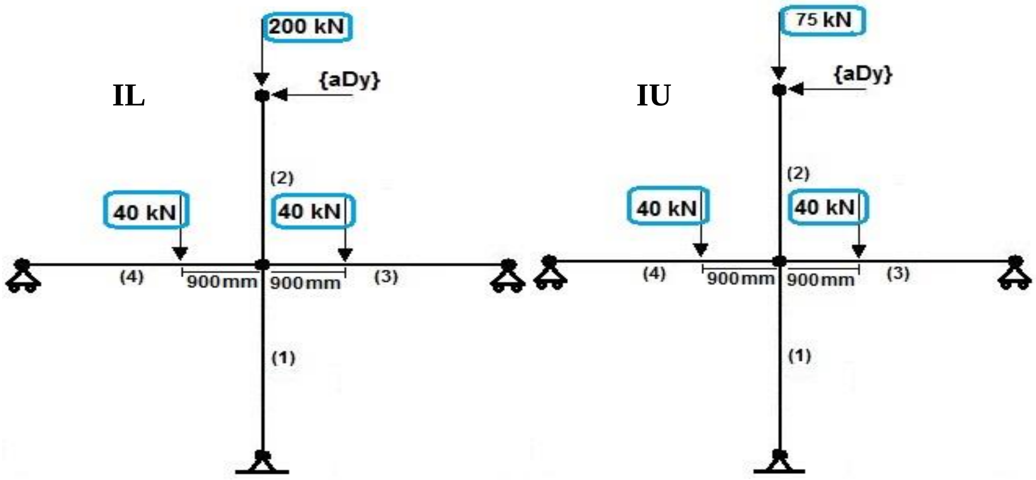

Figure 3.10. Gravity loading for the specimen IL and IU

Cyclic Pushover Analysis: Benavent-Climent's experiment employed a load history that consists of several sets of three cycles of forced horizontal displacements at the top of the column. The amplitude of the cycles was made constant within each set but increased with every consecutive set of cycles following the sequence 0.5Δy, 0.75Δy, 1.0Δy, 2Δy, 3Δy, 4Δy and so on, up to the maximum stroke of the actuator. Here, Δy is the predicted yield displacement defined as Δy = Qy/Ks predicted by Sugano's equation, which is already found as 59mm for the specimen IL and 34mm for UL. The actuator displacement histories of the experiment specimens are shown in Figure 3.11 and Figure 3.12 using a displacement recorder object in OpenSees.

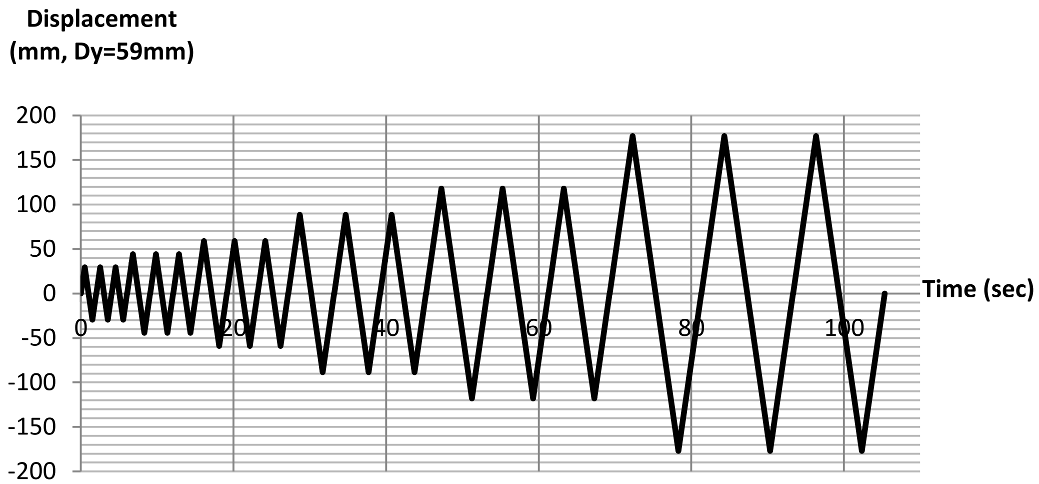

Figure 3.11. Cyclic displacement history of the actuator for the specimen IL

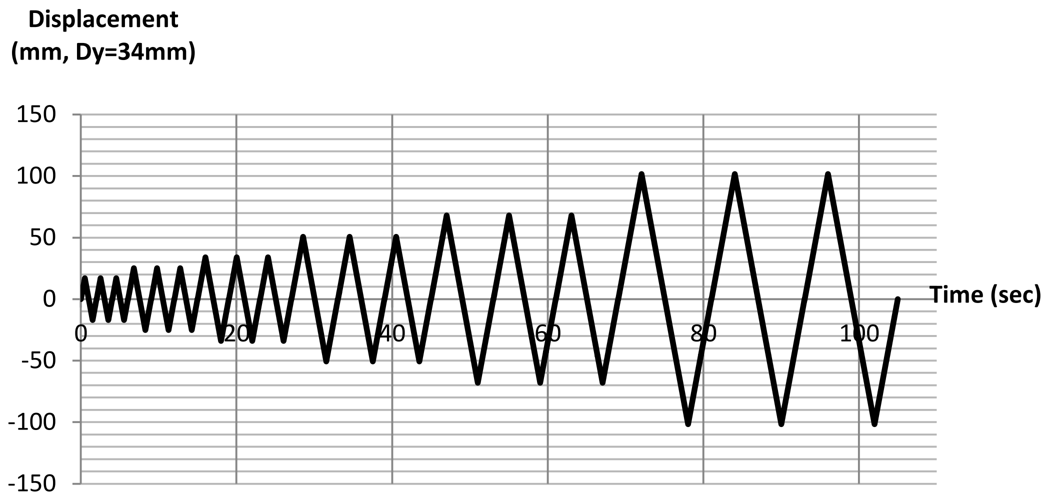

Figure 3.12. Cyclic displacement history of the actuator for the specimen IU

The number of displacement cycles for OpenSees cyclic pushover analyses is selected so that same number of cycles occurs in the simulated hysteresis with the experimental results. However, the figures that show the hysteresis cycles in the experimental output employed fewer displacement cycles. Therefore, the calibrated cycles are matched as they have the same number of cycles

3.4.2. Li and Kulkarni (2010) Specimen EWB1

Li and Kulkarni (2010) developed a set of external wide beam connections for different section geometries. In this report, the external specimen EWB1 is modelled with a similar approach applied to the experimental specimens of Benavent-Climent (2010). The experimental specimen geometry and reinforcement details of Li and Kulkarni (2010) are displayed in Figure 3.13.

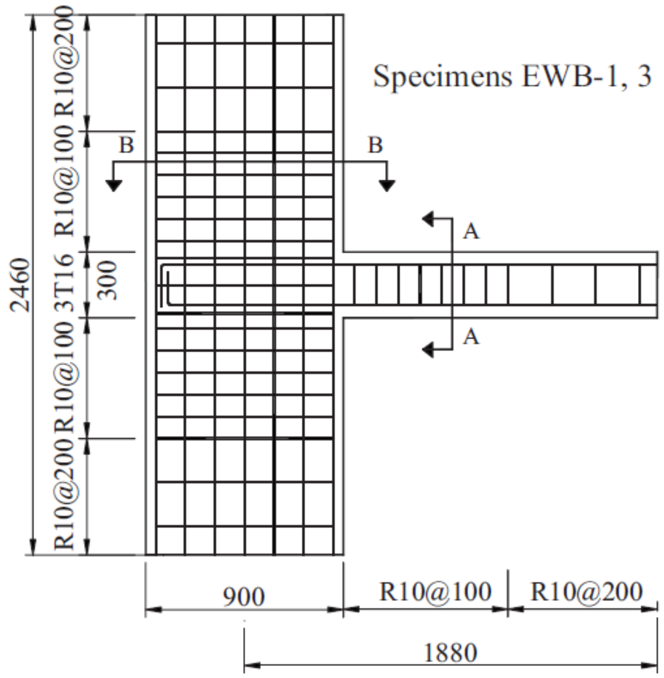

Figure 3.13. Geometry and reinforcement details of the wide beam column connection specimen EWB1 (Li and Kulkarni, 2010)

Longitudinal reinforcement for the beam, columns, and transverse beams consisted of deformed bars characterized by its yield strength f_y of 460 MPa. Bar diameters of longitudinal reinforcement were varied from 25 to 16 mm. Compressive strength of concrete targeted during the design phase was 70 MPa for EWB1. The average compressive strength of concrete f_c obtained from the concrete cylinder samples, was found to be 64.1 MPa for EWB1.

3.5. Calibrations of the Wide Beam Connections

The calibration steps are only given for specimen IL and only the final calibration is provided for all other specimens.

Step 1: The yield moments My+ and My- are predicted using the approach developed by Panagiotakos and Fardis (2001). The input parameters are given in Table 3.4 and the predicted yield moments are given in Table 3.5 and Table 3.6.

Step 2: As the second step of calibration, the initial stiffness Ke is estimated using Haselton's equation. The equation is basically another form of Fardis' estimation. It is the secant value of effective stiffness to 40% of the yield force of the component.

Table 3.2. Initial Stiffness Estimation of the Specimen IL

Spec.	Member	K_e (kN.m^2)
IL	Column	3019.0
	Beam	1635.3

Step 3: Plastic Rotation Capacity is determined using Haselton's equation as given in section 3.3.2.

Step 4: Post Capping Rotation Capacity is determined using Haselton's equation as given in section 3.3.2.

Step 5: Strain Hardening Ratios is determined using Haselton's equation as given in section 3.3.2.

The calibration parameters are calculated as in Table 3.3.

Table 3.3. Ibarra-Krawinkler calibration parameters for the specimen IL

Spec.	Member	K_e (kN.m)	M_y^+ (kN.m)	M_y^- (kN.m)	θ_p (rad)	θ_{pc} (rad)	θ_{tot} (rad)	M_c/M_y
IL	Column	4705.5	48.2	48.2	0.029	0.044	0.039	1.20
	Beam	3199.5	35.1	56.4	0.039	0.072	0.050	1.22

Table 3.4. Material and geometry input parameters for yield moment prediction

Spec.	Member	b (mm)	d_{eff} (mm)	fc' (Mpa)	d' (mm)	ρ	ρ'	ρ_v	fy (Mpa)
IL	Column	270	245	24.9	25	0.0165	0.0165	0.00314	420
	Beam	480	155	24.9	25	0.0118	0.0196	0.00377	420

Table 3.5. Prediction of yield moment M_y^+

Spec.	Member	A	B	ξ_y	$Ø_y$ (mm^{-1})	δ'	n (E_s/E_c)	E_c (Mpa)	M_y (kN)
IL	Column	0.0447	0.0285	0.4124	1.87E-05	0.10204	8.4379	23702.5	163.93
	Beam	0.0353	0.0173	0.3191	3.82E-05	0.16129	8.4379	23702.5	105.90

Table 3.6. Prediction of yield moment M_y^-

Spec.	Member	A	B	ξ_y	$Ø_y$ (mm^{-1})	δ'	n (E_s/E_c)	E_c (Mpa)	M_y (kN)
IL	Column	0.0447	0.0285	0.4124	1.87E-05	0.10204	8.4379	23702.5	163.93
	Beam	0.0353	0.0238	0.4028	3.03E-05	0.16129	8.4379	23702.5	114.93

Step 6: In this step of calibration, the monotonic backbone curve is further calibrated by multiplying the estimated parameters M_y, K_e and θ_p by a correction factor. Although the above predictions produce close estimates, many deficiencies of wide-beam column connections are omitted in the prediction equations. The correction factors are provided from the research study of Benavent-Climent (2007) where the comparisons were made between the backbone curves of wide-beam column connections and conventional beam column connections. Pushover analysis is held to accommodate a better calibration. The monotonic curve is plotted to see how well the backbone curve fits the real hysteresis curve. The base case in Figure 3.14 consists of the hysteresis parameters calculated in Table 3.3. On the other hand the calibrated case in Figure 3.15 consists of the factored calibration parameters.

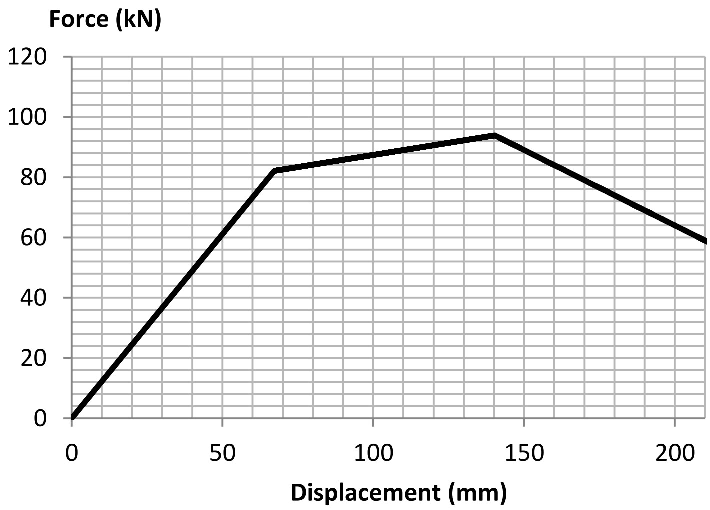

Figure 3.14. Pushover curve for the base case ($1.0M_y$, $1.0K_e$, $1.0\theta_p$)

The monotonic behavior is calibrated by multiplying correction factors with the estimated values. According to the experimental results of Benavent-Climent (2010), My ≈ 70kN, Ke ≈ 1750 kN/m, μ ≈ 2.6. The corrected monotonic behavior of the computer model of the wide-beam connection is matched with the experimental output in Figure 3.15.

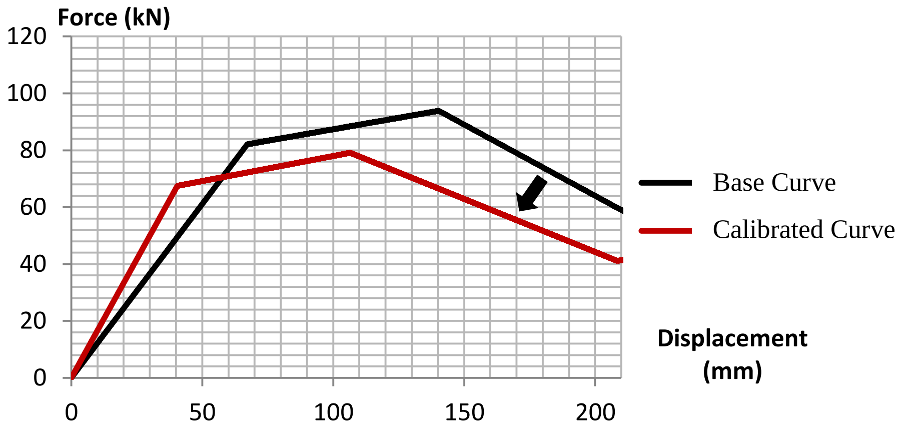

Figure 3.15. Pushover curve for the calibrated case ($0.85M_y$, $1.4K_e$, $0.9\theta_p$)

Step 7: In this final step, the calibration requires an iterative process in order to determine cyclic deterioration parameters. The calibration step continues until the deterioration parameters λ_A, λ_K, λ_S and λ_C produce acceptable matches for all simulated specimens. The base case (without step 6 and 7) is shown in Figure 3.16 for illustration purpose. The cyclic deterioration parameters are predicted as default values of $\lambda_A = \lambda_K = \lambda_S = \lambda_C = 1.0$ meaning full deterioration in all modes.

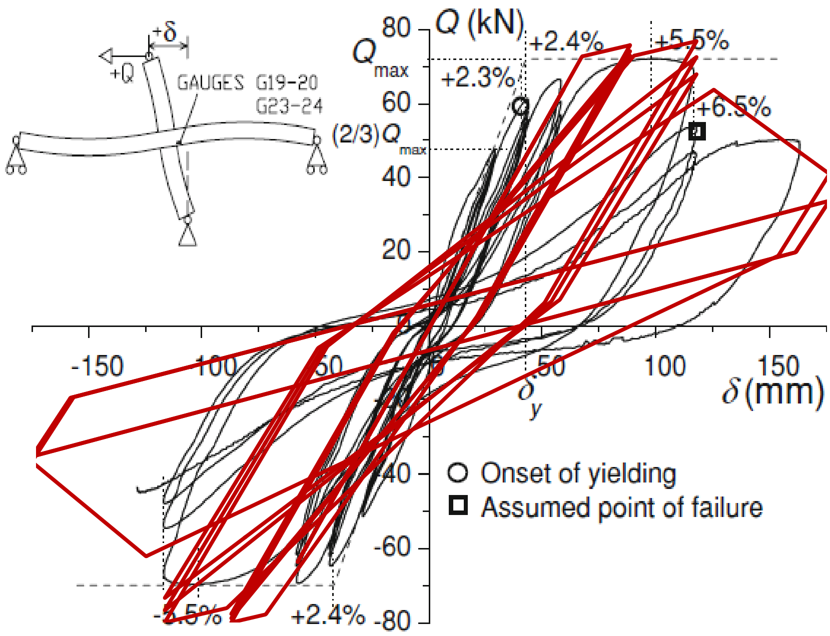

Figure 3.16. Hysteresis response of the specimen IL (Base case)

Calibration 1: Yield moment, initial stiffness and plastic rotation values are corrected as, 0.85My, 1.4Ky, 0.9θp. The updated hysteresis is shown in Figure 3.17.

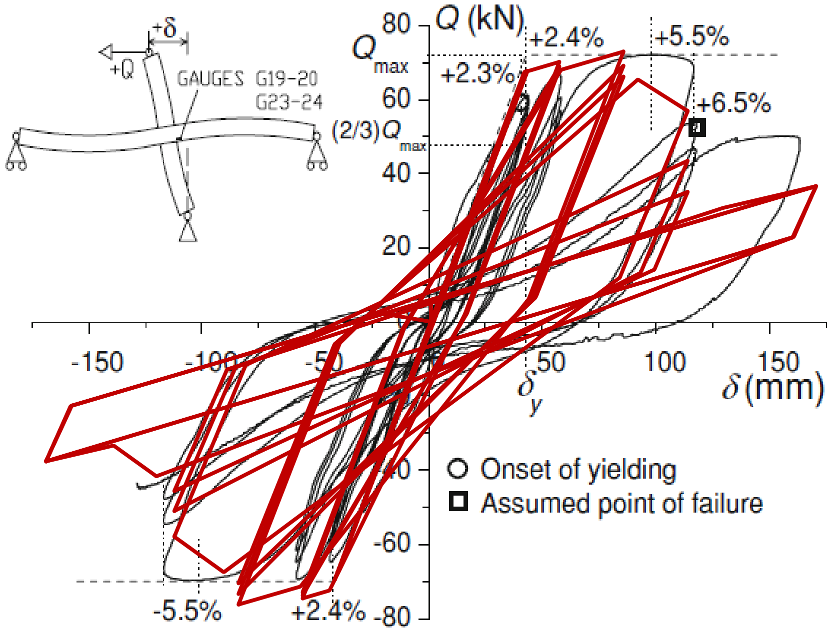

Figure 3.17. Hysteresis response of the specimen IL (1st calibration)

Calibration 2: Post-capping strength deterioration parameter λ_C is calibrated. A value between 1.0-5.0 (medium deterioration) gives an acceptable calibration.

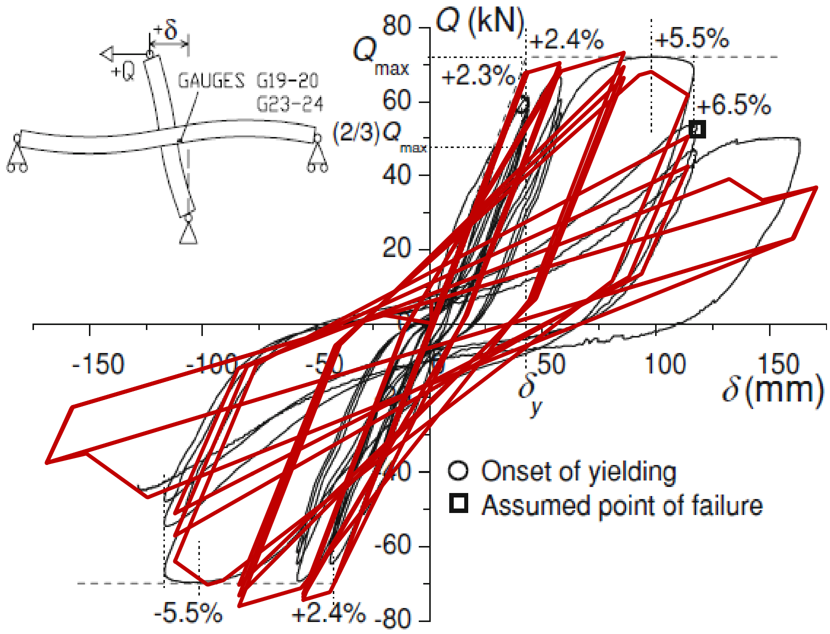

Figure 3.18. Hysteresis response of the specimen IL (2nd calibration)

Calibration 3: The other deterioration parameters are optimal as in the base case. $\lambda_A = \lambda_K = \lambda_S = 1.0$ present a full deterioration in related modes.

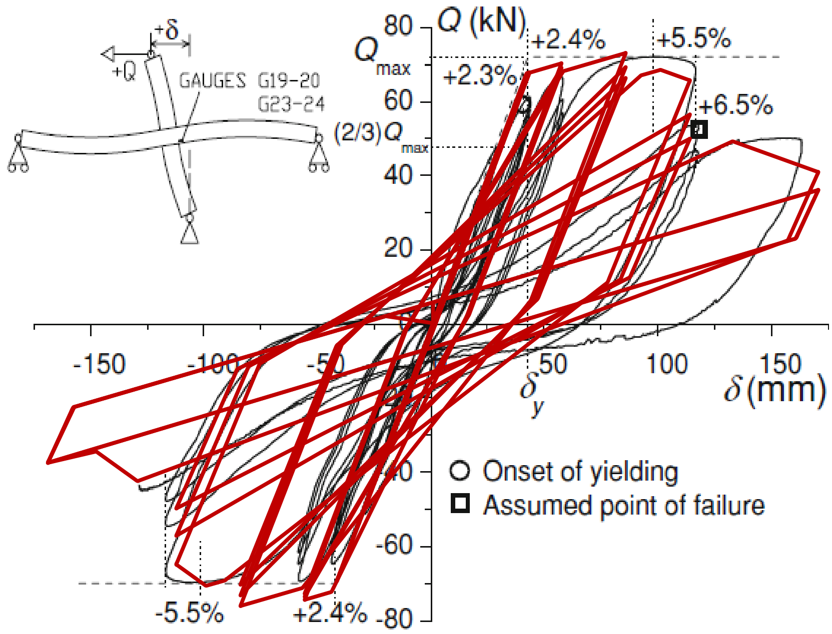

Figure 3.19. Hysteresis response of the specimen IL (Final calibration)

Post-capping rotation capacity determines the starting location of the negative stiffness trend in the hysteretic cycles. However, the strength deterioration parameter λ_C forces this point to shift toward the right on the hysteresis cycle. The angled shape occurs when this deterioration parameter is high meaning that the specimen has reached its ultimate displacement capacity.

Specimen IU has shorter wide-beam and weaker columns than the specimen IL. The OpenSees model of the connection specimen IU is similarly calibrated to the experimental output by following the previously defined procedure. The final hysteresis match after the calibration steps is given in Figure 3.20. The estimated calibration parameters matched quite well with the real hysteresis curve. Cyclic deterioration parameters also demonstrate compatible range of values (full deterioration in all cyclic parameters except post capping strength deterioration parameter).

The hysteresis curve for the specimen IU demonstrates pinched behavior due to active participation of the bar slip parameter of weak connections. The final calibration is shown in Figure 3.20.

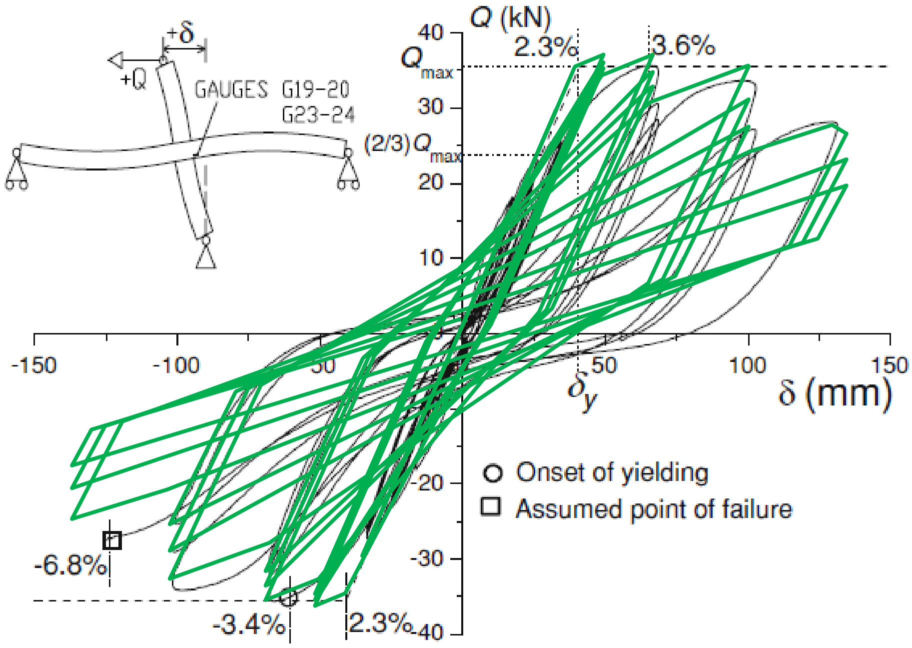

Figure 3.20. Hysteresis response of the specimen IU (Final calibration)

Li and Kulkarni (2010) set up full-scale exterior wide beam column connections and investigated their behavior under cyclic loading. The hysteresis behavior is modelled using the same procedure defined in the beginning of this report. The connection has relatively high stiffness due to columns' large effective depth. The calibration parameters predicted the cyclic behavior quite well yet the reverse unloading branch did not demonstrate a proper trend. This is mainly due to high stiffness and inability to control the unloading stiffness deterioration parameter within the Modified Ibarra Krawinkler model. The calibration is also compared with the model developed in the paper. DIANA software (Version 7 - 2000) is used by including the exterior wide beam zone and the bar slip behavior using a tie-strut joint model. The hysteresis calibration in the OpenSees simulation of the experimental specimen EWB1 presented as successful a match as the calibration conducted by Li and Kulkarni (2010). Both matches are shown in Figure 3.21 and Figure 3.22.

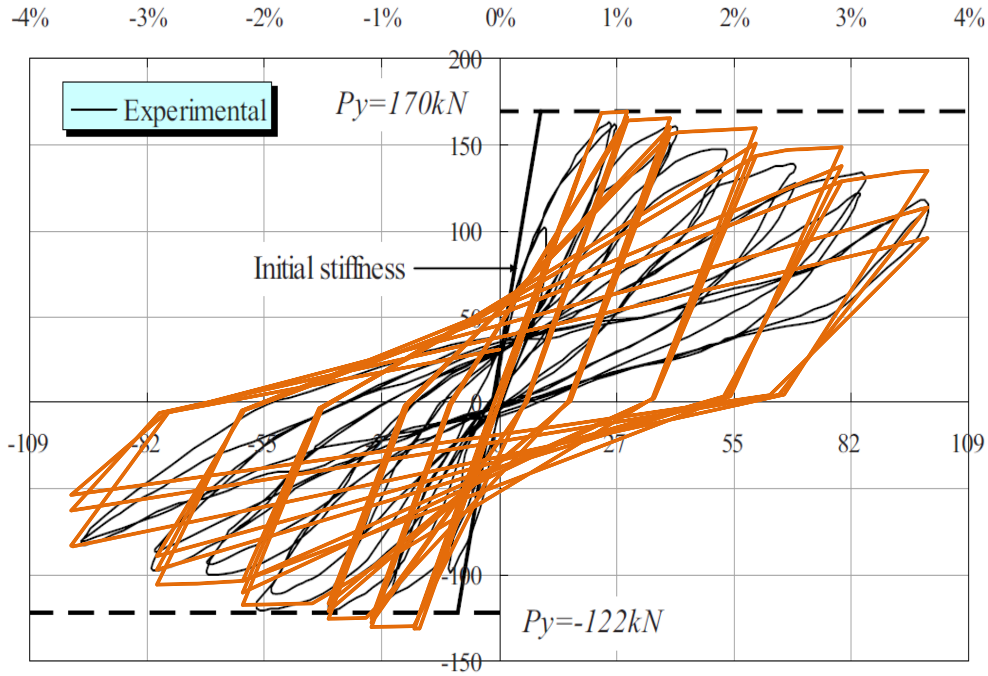

Figure 3.21. Calibration of EWB1 using OpenSees (Final calibration step)

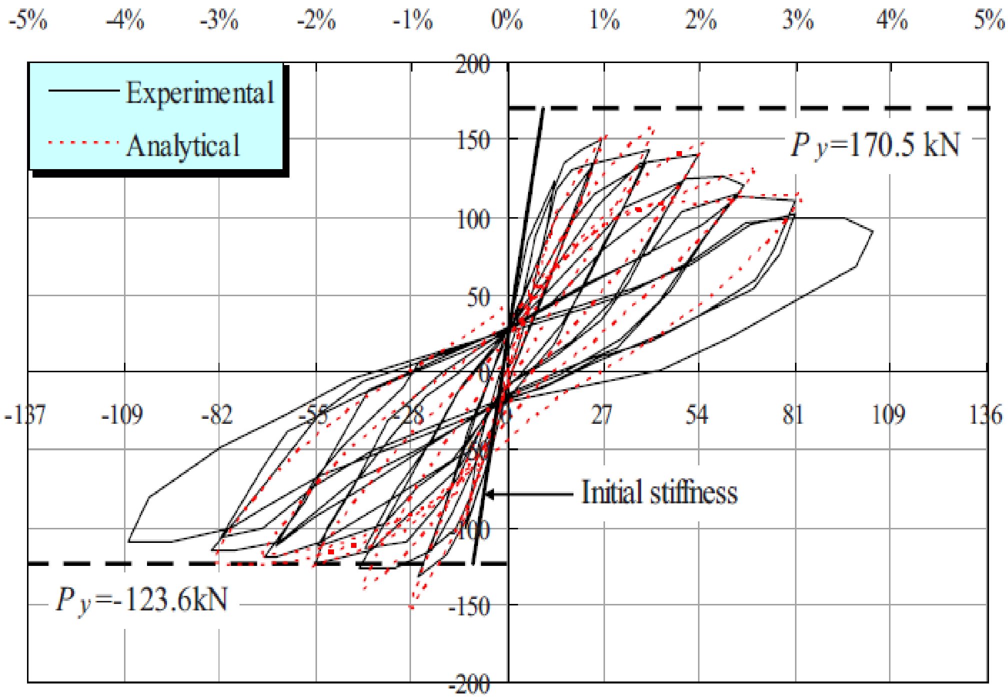

Figure 3.22. Calibration of EWB1 using Diana software (Li and Kulkarni, 2010)

In this thesis section, three different wide-beam column connections were modelled in OpenSees and their hysteretic behavior was simulated by calibrating the model parameters of Modified Ibarra-Krawinler Deterioration Model through a generalized calibration procedure. Two of the experimental specimens were internal wide-column connections studied by Benavent-Climent (2010) and the other experimental specimen was an external wide-beam column connection studied by Li and Kulkarni (2010). The calibration procedure predicts the parameters for both the monotonic behavior and the cyclic behavior of the experimental specimens. Whereas the analytical predictions that belong to the monotonic behavior need to be repeated for each wide beam connection simulation; the calibrated values for cyclic deterioration parameters found after iterative calibrations can be readily used for future simulations.

The calibration study also showed that the interior wide-beam column connections are likely to present positive post yield stiffness in their monotonic backbone curves. On the other hand, the post yield trend of the external wide-beam column connections followed a negative stiffness line. Furthermore, the external wide-beam column connection of Li and Kulkarni (2010) presented more pinched hysteresis due to significant bond slip behavior in the experiments. Yet the deterioration model was not capable of including this clear pinching. Hence, the deficient behavior of wide beam column connections is more evident in the external wide-beam column connections and therefore, considerable post yield degradation was observed in the external wide-beam connection specimen of Li and Kulkarni (2010).

The simulation of wide beam column connections by conducting a calibration study to the experimental hysteresis behavior of past research studies enables a realistic investigation of this type of structures. Thereby, simulation of the connection level behavior can be applied to the full-scale simulation of a wide beam frame building.

CHAPTER 4

VULNERABILITY ANALYSIS OF WIDE-BEAM BUILDINGS

4.1. General

In this chapter, vulnerability analysis for a planar wide beam building model, for which geometrical and material properties are based on Turkish construction practice, is carried out. First, the seismic capacity of the building model is determined in terms of the performance limits of immediate occupancy (IO), life safety (LS) and collapse prevention (CP) on the capacity curve obtained from the pushover analysis. After the attainment of limit states, seismic demand is quantified by nonlinear response through time-history analyses. These analyses are conducted by using a set of selected ground motion records. The fragility curves are then obtained by calculating the probabilities of exceeding each limit state for specified levels of ground motion intensity. Finally, the obtained results are compared with the results of previously studied RC frame buildings of similar types.

4.2. Wide-beam building frame model

A full-scale, 5-story, 4-bay, two dimensional wide-beam frame structure that considers the typical geometrical and material properties of Turkish wide-beam frame construction practice, is modelled in OpenSees by assigning joint behavior to the rotational springs. These springs were previously calibrated within Modified Ibarra Krawinkler Hysteresis Model. The structural, material and loading properties are described below.

Typical wide-beam structures in Turkey have 2-4 bays and 3-6 stories of which the story heights range between 2.7m – 3.0m. The ground stories are typically 1.1 to 1.4 times higher than the other stories. Wide-beam depth ranges between 30cm - 32cm whereas the width is mostly 50cm. Nominal concrete strength is characteristically

30MPa and the steel reinforcement yield strength is 420 MPa. The columns have rectangular sections with typical dimensions of 20x50cm, 25x60cm, 30x60cm and 30x70cm. (Dönmez, 2013)

4.2.1. Selected Model Parameters

The model parameters are selected according to the study carried out by Dönmez (2013). The compatibility with the current earthquake code (TEC 2007) is also maintained. The floor and the cross-section layouts are shown in Figure 4.1 and Figure 4.2 respectively.

Building geometry parameters are selected as following:

- Number of Stories: 5
- Number of Bays: 4
- Bay Width: 6.0m
- Ground Story Height: 4.0m, Typical Story Height: 3.0m

The section geometry parameters are then selected:

- Wide-beam Width: 500mm
- Wide-beam Depth: 320mm
- Column Width: 300mm
- Column Depth: 600mm
- Infill Wall Thickness: 150mm

The material parameters are defined as following:

- Nominal Concrete Strength: 30MPa
- Steel Reinforcement Yield Strength: 420MPa
- Concrete Elastic Modulus: 31800MPa
  (TS500-2000 approximation: $3250\sqrt{f_{cj}} + 14000$)
- Steel Elastic Modulus: 200,000MPa
- Elastic Modulus of Infill Walls: 3100MPa

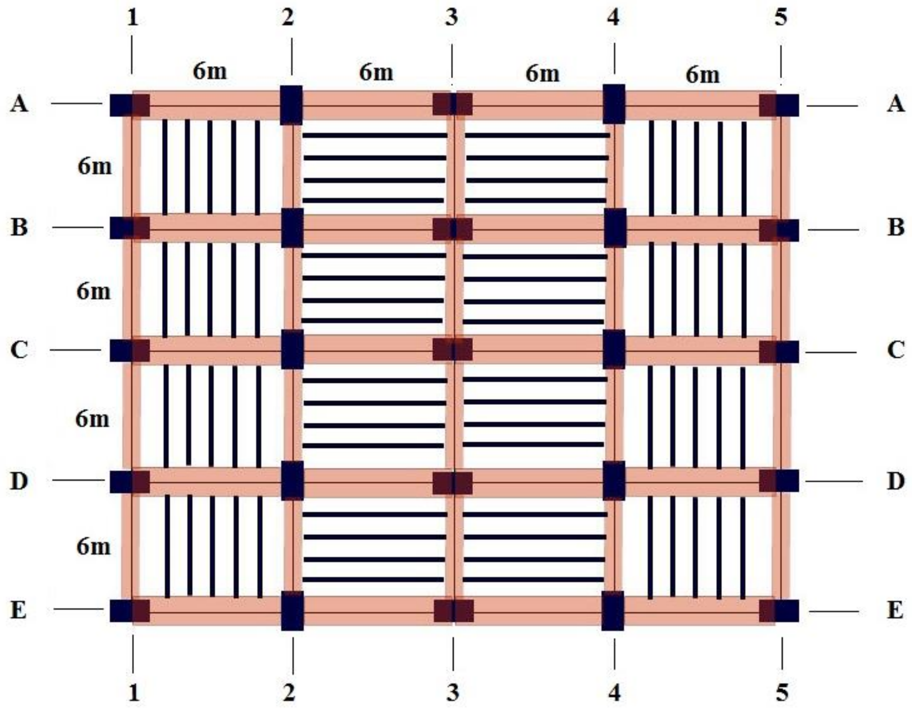

Figure 4.1. Floor layout of the selected wide-beam frame building

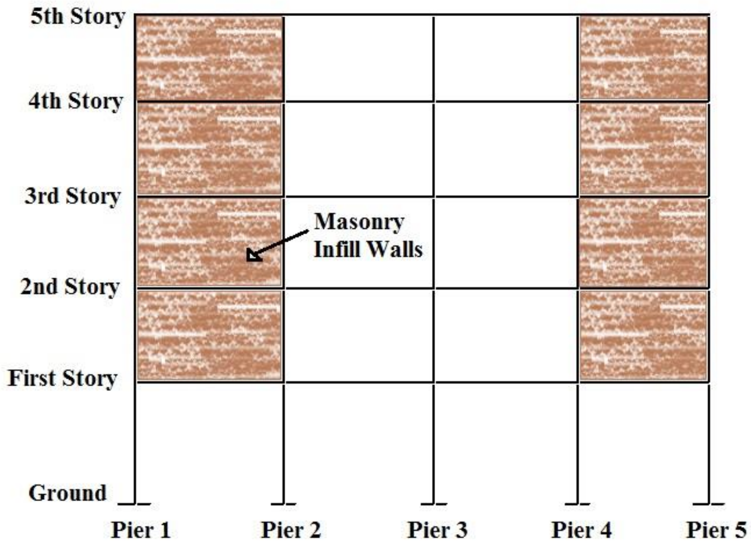

Figure 4.2. Cross-section layout from section B-B

Whereas joists span in wide-beam direction in the interior bays, they span in the opposite direction in the exterior bays. The masonry infill wall are only present in the exterior bays except the ground floor.

4.2.2. Estimated Loads and Masses of the Wide-Beam Building

Loads and masses are estimated in Table 4.1 showing the details of calculation for belonging to slabs, beams, columns and infill walls.

Table 4.1. Load calculation table of the selected wide beam frame building

Slab/Member	Weight Calculation
Concrete Slab	0.07m x 25kN/m^3 = 1.75kN/m^2
Floor Finishes	0.05m x 22kN/m^3 = 1.10kN/m^2
Surfacing	0.02m x 27kN/m^3 = 0.54kN/m^2
Plaster	0.02m x 20kN/m^3 = 0.40kN/m^2
Ribs	2(1.0 x 0.1 x 0.25m) x 25kN/m^3 = 1.25kN/m^2
Infill Blocks	(0.2+0.4+0.2) x 1.0kN/m^2 = 0.8kN/m^2
Live Load	0.3 x 3.5kN/m^2 = 1.05kN/m^2
Total Slab Weight =	6.89kN/m^2
Columns (1st Story)	(0.3 x 0.6 x 4.0)m^3 x 25kN/m^3 = 18kN
Columns (Other stories)	(0.3 x 0.6 x 3.0)m^3 x 25kN/m^3 = 13.5kN
Beam Members	(0.32 x 0.5)m^2 x 25kN/m^3 = 4kN/m
Masonry Walls	(3.0m -0.3m) x 1.0kN/m^2 = 2.7kN/m
Total Building Weight =	(6.89kN/m^2 x 576 m^2 x 5) + (25 x 18kN) + (100 x 13.5kN) + (100 x 6.0m x 4kN/m) + (100 x 6m x 2.7kN/m) ≈ **25700kN**

The weight of wide-beam slab is calculated by considering that the joists span in one direction and the calculation is carried out for one meter length of typical slab section shown in Figure 4.3. There are two lines of ribs and two lines of infill blocks in 1m length of slab section.

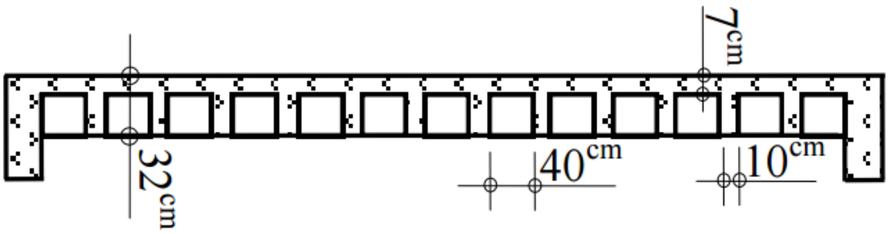

Figure 4.3. Slab section of the wide-beam building

As the goal of the research study was to investigate the wide-beam connections in their strong axis, the selected building will be studied in only one direction, paralel to the wide beams. Although the building may pose higher risk under earthquake excitation in the transverse direction, it would not be reliable to model the building in that direction; because the wide-beam connection simulation is developed based on the calibration of the hysteresis behavior of wide-beam column connections in their strong axis. Therefore, a 2D model is built to analyze an internal wide-beam frame (B-B section). The building weight is distributed over the frames so that a two-dimensional analysis can be carried out. Since, the joists span in the wide-beam direction in the interior bays, the slab loads are transferred to the transverse beams. These loads are acted on the columns as point loads. However, in the exterior bays, the slab loads are transferred to the wide beams through the joists spanning in the transverse direction. Rectangular load distribution is assumed for distribution of the slab loads. The masonry infill walls also exist in the all exterior bays except the ground floor. Their weights are also applied on wide beams as distributed gravity loads. The 2D wide-beam internal frame model with all applied loads is displayed in Figure 4.4.

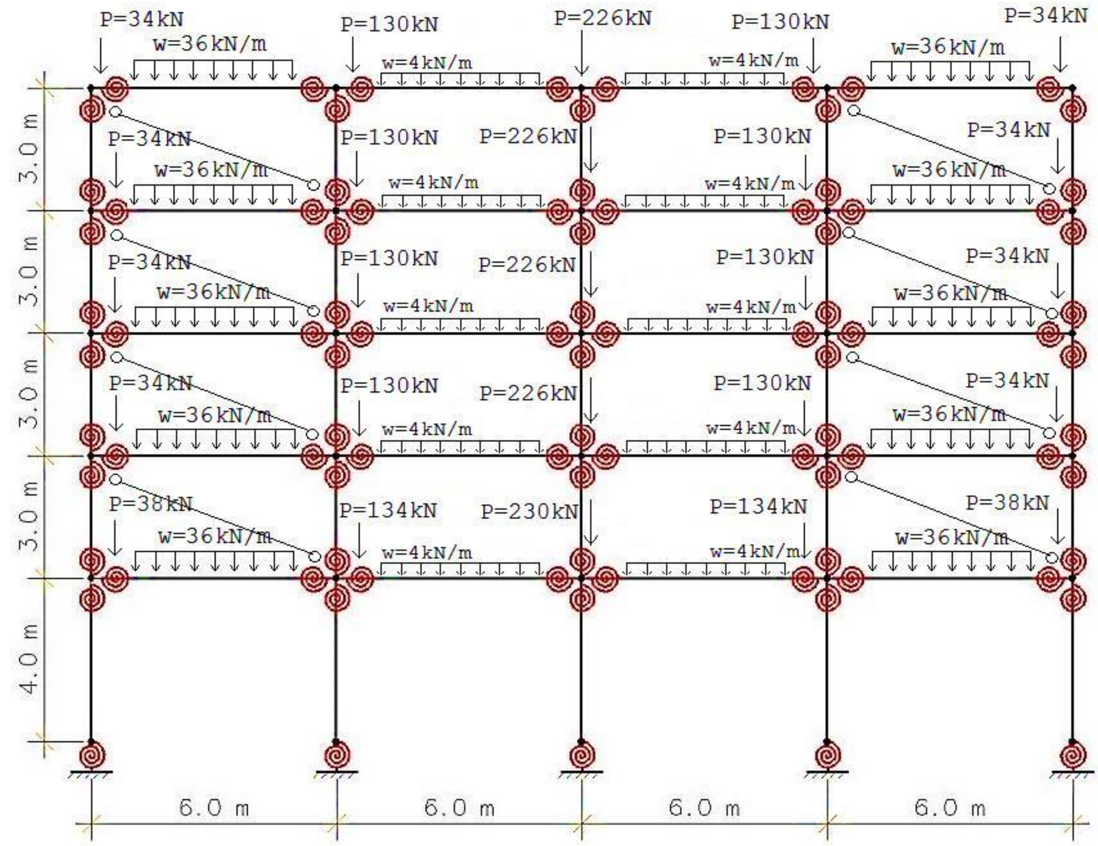

Figure 4.4. 2D frame model of the selected wide-beam building

The model building frame is composed of linear beam column elements whose stiffness was defined in terms of the inertia and the element section area. Nonlinear behavior is simulated by the rotational spring elements defined at the member ends. These spring elements are modelled with zero length elements constrained to the joint nodes in translational degree of freedoms. The nonlinear material of the spring elements is the same deterioration model studied in Chapter 3.

4.2.3. Modelling of the Infill Walls

The analysis requires an accurate way to employ structural contribution of the masonry infill walls. Macro-models allow for the representation of infill panel behavior and its influence on a building's structural response (Riddington and Stafford Smith, 1977). The most commonly used macro-model is the equivalent single diagonal strut model. In this model, the walls are considered as infill panels which are to be converted into equivalent strut elements. Mainstone (1970) developed an easy and efficient method for calculating the effective diagonal strut width based on experimental tests. This model is implemented into the OpenSees model source code. However, a more complex material model (Uniaxial Pinching 4) is used to define the monotonic and cyclic behavior of equivalent struts (Rodrigues et al., 2010).

The infill material properties, wall thickness, column and beam lengths as well as their section geometries are the main parameters in the employed macro-model. Mainstone and Weeks (1970) developed empirical equations based on experimental and analytical data. The formula was also used by FEMA 274 (1998) and FEMA 306 (1998). The parameters for the single strut model are depicted in Figure 4.5.

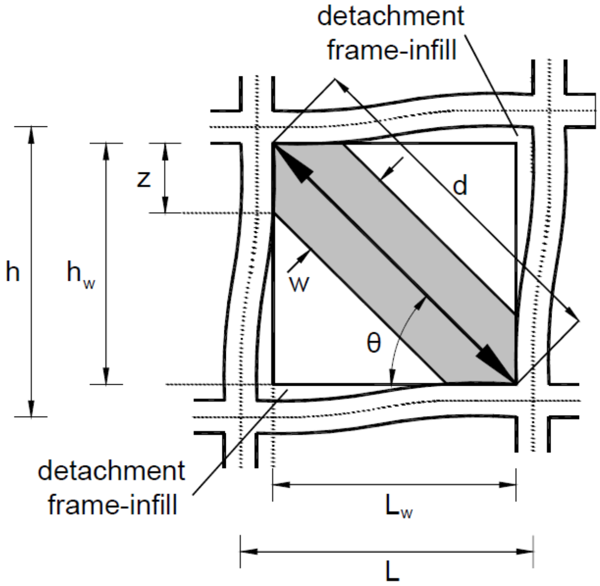

Figure 4.5. Masonry infill frame sub-assemblage (FEMA 306, 1998)

The effective infill width is calculated through the following formula.

$$\frac{w_{inf}}{d_{inf}} = 0.175\lambda_h^{-0.4}$$

(4.1)

Where;

d_{inf}: Diagonal length of the infill wall

λ_h: Panel-to-frame stiffness parameter

The panel-to-frame stiffness parameter is calculated as follows.

$$\lambda_h = h\sqrt[4]{\frac{E_w t_w \sin 2\theta}{4EIh_w}}$$

(4.2)

Where;

t_{inf}: Infill panel thickness

E_{inf}: Elastic modulus of the infill panel

h_{inf}: The height of the infill wall

The material model is a pinching hysteresis material with four piece-wise linear envelope components. The calibration is performed based on the experimental studies of Dolsek and Fajfar (2008).

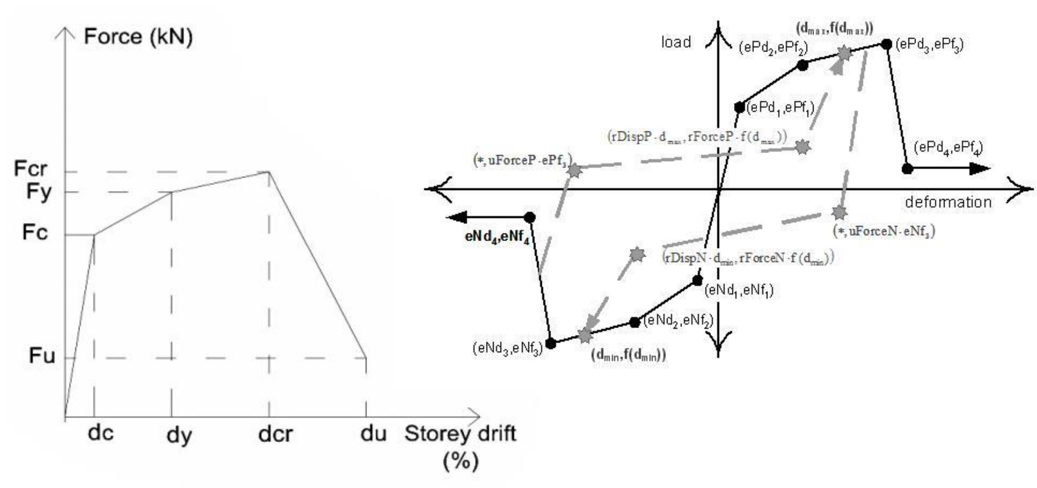

Figure 4.6. Material model used in the calibration (Rodrigues et al., 2010)

4.2.4. Drift Check for the Earthquake Code (TEC 2007)

Since the goal of this study is to adress the deficiencies in the earthquake code regarding the use of wide beam systems in buildings, the selected wide beam building to be analyzed should comply with the current earthquake code so that deficiencies in the code can be exposed. TEC 2007 (Turkish Earthquake Code, 2007) earthquake design requirements are checked for the model frame building as in the following.

- Total Equivalent Earthquake Load: $V_t = W.A(T_1)/R_a$ (4.3)
- Total Building Weight: $W_i = G_i + n\ Q_i$ (4.4)

Where; n=0.3 for live load contribution.

w_5: 1034kN (Total floor weight on the roof)
w_4: 1034kN (Total floor weight on the 4^{th} floor)
w_3: 1034kN (Total floor weight on the 3^{rd} floor)
w_2: 1034kN (Total floor weight on the 2^{nd} floor)
w_1: 1054kN (Total floor weight on the 1^{st} floor)

W = 5200kN

- Spectral Acceleration Constant: $A(T_1) = A_0.I.S(T_1)$ (4.5)

Where; $A_0 = 0.4$ for 1st degree earthquake region.

- Building Importance Factor: 1.0 for residential buildings
- Spectrum Constant $S(T_1)$:

  $S(T)= 1+1.5\ T/T_A$ $(0 \leq T < T_A)$ (4.6.a)

  $S(T)= 2.5$ $(T_A \leq T < T_B)$ (4.7.b)

  $S(T)= 2.5\ (T_B/T)^{0.8}$ $(T > T_B)$ (4.8.c)

- Spectrum Characteristic Periods:
  - Local Soil Class: Z4
  - T_A= 0.20 sec ve T_B= 0.90 sec for Z4 Soil Class
  - Natural Period Prediction: T_1= 0.79 sec (Calculated in OpenSees)
  - $A(T_1)$= 0.40x1.0x2.5 = 1.0

The natural period of the frame structure was calculated by the modal analysis carried out in OpenSees.

- Total Earthquake Load: $V_t = 5200 \mathrm{x} 1.0 \mathrm{x} \frac{1}{8} = 650$ kN
- Equivalent EQ loads on each story

$$F_i = (V_t - \Delta F_N).\frac{W_i.H_i}{\sum_{i=1}^{N} W_i.H_i} \tag{4.9}$$

$$\Delta F_N = 0.0075NV_t = 24.375 \text{ kN} \tag{4.10}$$

Where, ΔF_N is the lateral force acting on the roof. The lateral loads and the inter-story drifts are calculated through the equivalent lateral load analysis as in Table 4.2 and in Table 4.3 respectively.

Table 4.2. Equivalent lateral loads acting on the frame

Floor	**W_i (kN)**	**H_i (m)**	**$W_i.H_i$ (kN.m)**	**F_i (kN)**
1	1054	4	4216	51
2	1034	7	7238	87
3	1034	10	10340	125
4	1034	13	13442	162
5	1034	16	16544	224

Table 4.3. Story drifts calculated from the analysis

Floor	**δ_i (mm)**	**Δ_i (mm)**	**Δ_{ieff} (mm)**	**h_i (m)**	**Δ_{imax}/h_{imax}**	**Check**
1	8.9	8.9	71.5	4	0.018	OKAY
2	15.2	6.3	50.3	3	0.017	OKAY
3	20.0	4.8	38.5	3	0.013	OKAY
4	23.4	3.4	27.2	3	0.009	OKAY
5	25.9	2.5	19.7	3	0.007	OKAY

The drift check is carried out to ensure conformity to the requirement of $\Delta_{imax}/h_{imax} \leq 0.02$ according to TEC 2007, Section 2.10. Hence, the considered building model seems to conform to the drift limits of the latest Turkish earthquake code. However, these drift values would not indicate the real drift of the wide-beam frame, since all the characteristic behavior previously investigated in the connection level was assigned to the nonlinear rotational spring elements which are not defined for an elastic analysis. Namely, the procedure for the drift calculation in the earthquake code underestimates significantly the inter-story drifts for wide-beam frame structures, because the equivalent lateral load analysis in the code is applicable only to the conventional RC beam column buildings.

The design checks for the beam and column members are also carried out within the model building code in OpenSees. The minimum required reinforcement ratio for compression, tension and shear are calculated during the execution of material calibration code.

4.3. Pushover Analysis and the Capacity Curve.

Pushover analysis is carried to the wide-beam frame model by setting up a displacement controlled lateral static analysis procedure in OpenSees. The procedure includes the definition of the control node, the control degree of freedom, the maximum displacement and the displacement increment. The displacement control integrator object uses these variables and iterates over the Algorithm Newton object.

The pushover procedure also requires a very small initial lateral load that is applied to the displacement control node to prevent possible numerical integration errors. The lateral load pattern of the equivalent static lateral analysis in the drift check was used to define the initial lateral loads applied to all floors. These loads are defined at very small levels and it should not be confused with forced controlled pushover.

The capacity curve obtained from the pushover analysis is given in Figure 4.7. The spring damage conditions at corresponding maximum inter-story drift ratios are plotted on the capacity curve. The springs are named with the notation placed on the upper right corner. The yielded springs (the spring that has reached its yield rotation capacity) are colored in green and the capping springs (the spring that has reached its capping rotation) are colored in yellow. A failing spring which is colored in red is not observed during the pushover analysis.

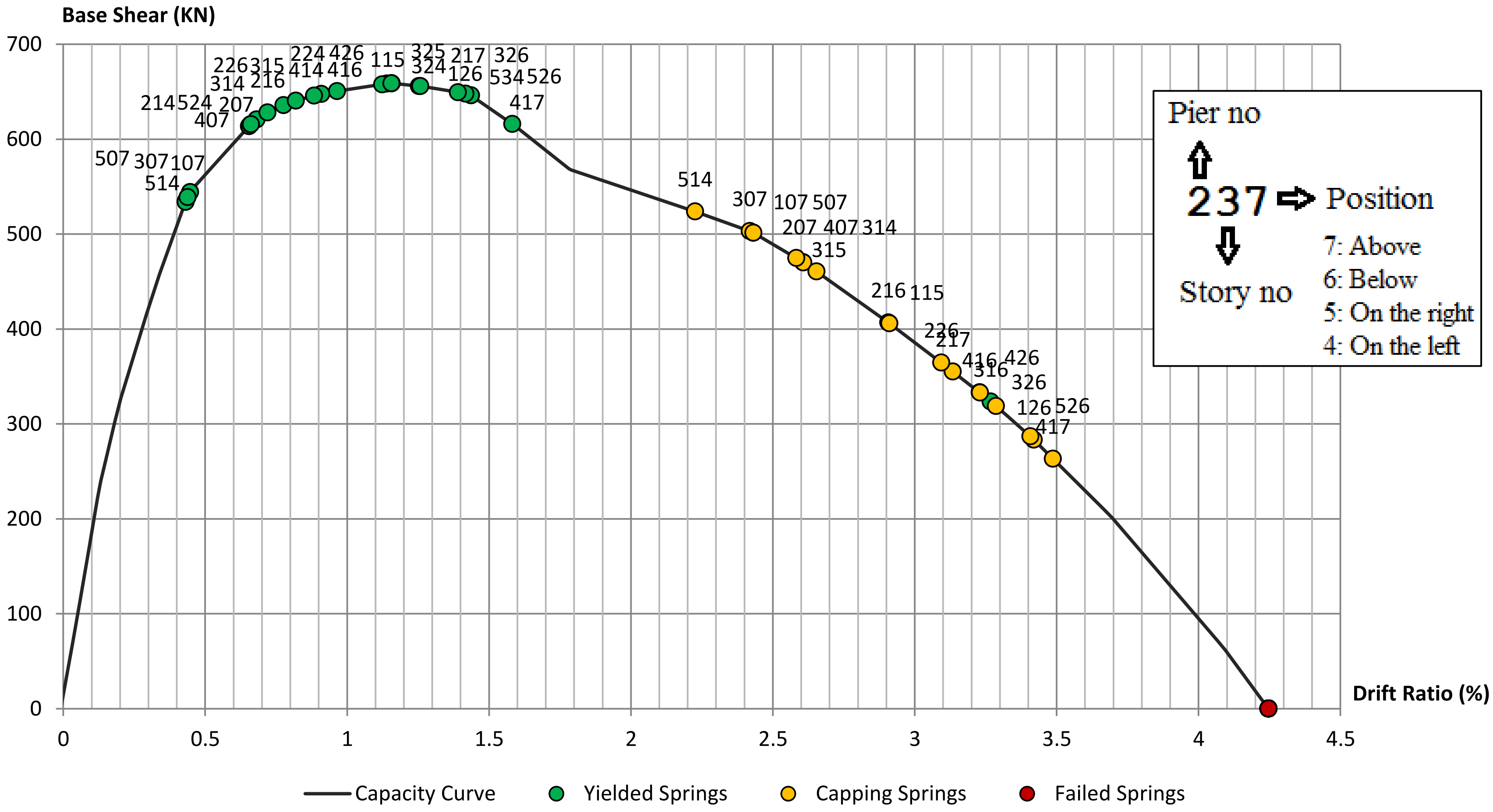

Figure 4.7. Pushover curve of the wide-beam building and spring deformations

4.4. Estimation of Deformation Limits

Deformation limit states, namely, the performance levels play a significant role in developing the fragility curves. These limit values are very effective in determining the fragility equation parameters especially for the wide beam frame systems for which the identification of limit states is highly dependent on the characteristics of the structure. It would be misleading to employ the performance levels defined for regular concrete frames in the case of wide beam frame buildings without regarding the inherent characteristics related to premature yielding of the wide beam connections and flexible behavior of the overall structure.

From engineering point of view, limit state is the point at which the system is no further capable of satisfying a performance level. There are different definitions of limit states for structural or nonstructural members in terms of both quantitative and qualitative expressions. To correlate post–earthquake condition of a structure to a performance parameter, strength degradation, damage, or possibility of repair can be employed. Usually, qualitative descriptions for structural performance levels are used in building codes. However, for design and analysis stages, the limit states should be given quantitatively in terms of either forces or deformations in structural or nonstructural members (Wen et al., 2003).

Estimating the deformation limits quantitatively is a very common approach for special types of construction such as wide-beam frame buildings. Although there is very limited fragility research on wide-beam buildings; several researchers quantitatively estimated the deformation limits in addition to code definitions in their research studies on wide-beam frame structures. Domínguez (2012) stated that the code based deformation limits overestimated the performance limit state values for wide-beam frame buildings. Similarly, López-Almansa et. al. (2013) concluded that the target drifts calculated according to FEMA 356 (2000) provided unreliable limit values when compared to the estimated values obtained with the first plastic hinge and the first failure.

The performance levels are quantitatively determined by considering the overall pushover behavior of the wide-beam frame building. The immediate occupancy deformation limit is defined as the first yield hinge mechanism. This damage state requires immediate occupancy after the earthquake with little or no plastic deformation. The ground story hinges yield as early as at 0.45% drift ratio. Therefore, immediate occupancy (IO) drift limit is selected as 0.45%. For the life safety drift limit, the maximum lateral load capacity is taken as reference. The overall capping of the structure occurs at 1.15% drift ratio. The life safety (LS) limit is then assumed as 1.15%. The collapse prevention (CP) limit is identified as the performance level where a capping hinge mechanism occurs in the system. At the deformation limit of 2.45% drift, all the ground story hinges reach their capping points and the structure exhibits immediate strength deterioration afterwards. Thus, collapse prevention (CP) drift limit is chosen as 2.45%.

Using these limit states values, the damage mechanisms at the prescribed limit states are shown in Figure 4.8, Figure 4.9, Figure 4.10 and Figure 4.11.

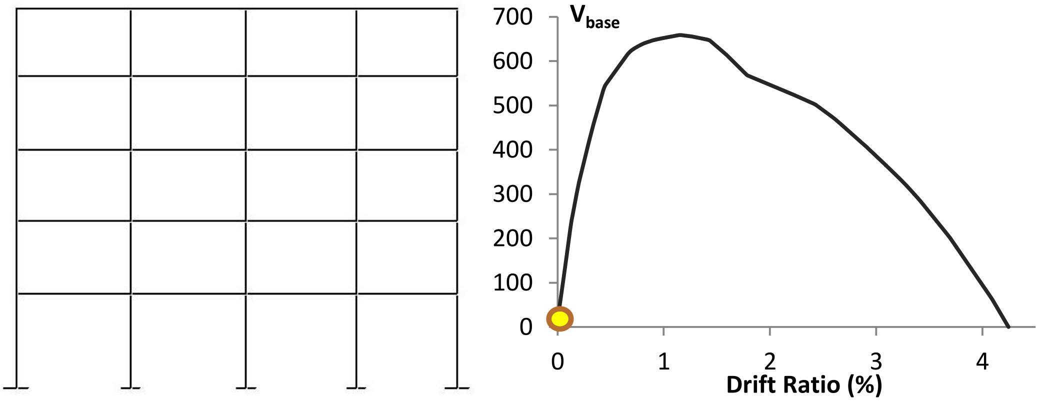

Figure 4.8. Damage mechanism at the initial state

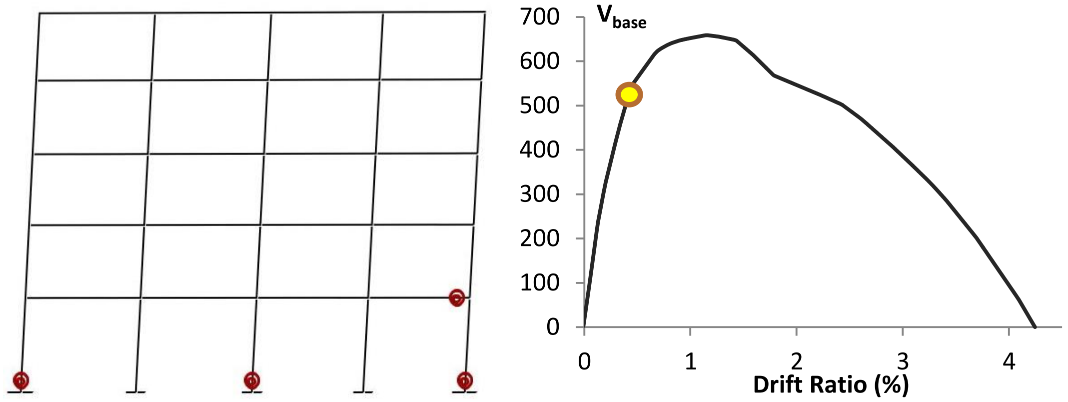

Figure 4.9. Damage mechanism at the immediate occupancy (IO) limit state

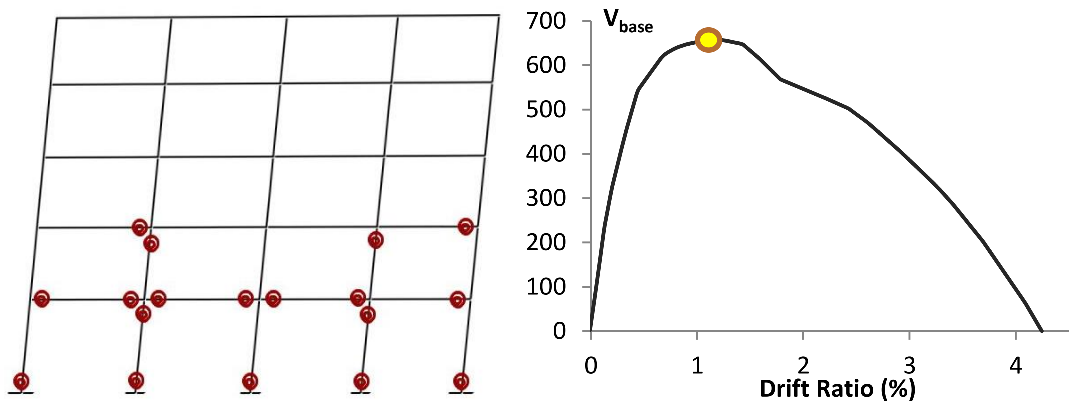

Figure 4.10. Damage mechanism at the Life Safety (LS) limit state

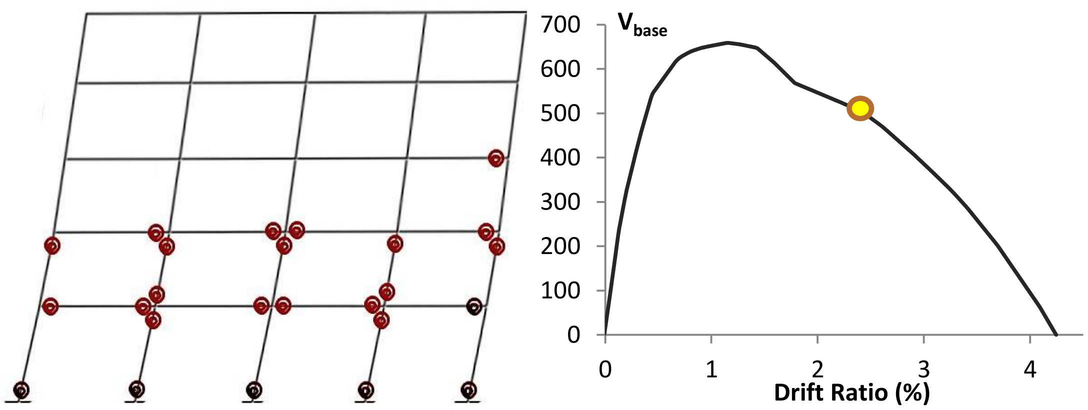

Figure 4.11. Damage mechanism at the Collapse Prevention (CP) limit state

4.2.5. Deformation Limits in Codes and Guidelines

Although quantitative deformation limits are used in the vulnerability study. The performance limits of three different seismic assessment guidelines are presented here for comparison. These quantitative limits are determined for low to mid-rise reinforced concrete frames not specifically for wide-beam frame structures. These guidelines are respectively American pre-standard, FEMA 356 (2000), European seismic code, Eurocode 8 (2003) and Turkish Earthquake Code (2007).

FEMA 356 (2000):

FEMA 356 (2000) is the American pre-standard and commentary for the seismic rehabilitation of buildings. The document presents deformation limits for both the global and the local assessments. The global level criteria are shown in Table 4.4.

Table 4.4. Inter-story drift limits based on FEMA 356 global-level criteria (percent)

Structure	Drift limits (%)		
	IO	LS	CP
Concrete frame	1	2	4 (2.9[a])
Concrete wall	0.5	1 (0.85[b])	2 (1.2[b])

[a] Punching shear, CP limited to 2.9% versus 4% based on punching shear prediction.
[b] Shear wall failure, LS and CP limited to 0.85% and 1.2% versus 1% and 2% based on shear wall failure in shear.

According to the table, the drift limit for the collapse prevention should be limited to 2.9%; since the wide-beam slab systems are vulnerable to punching shear under seismic loading;

Eurocode 8 (2003):

Eurocode 8 (2003) includes a part for the assessment of reinforced concrete columns that recommends the calculation of chord rotations with the given equations in the code. These equations are functions of many variables such as axial load ratio, longitudinal reinforcement ratio, transverse reinforcement ratio, and yield strength of the transverse reinforcement. In Eurocode 8, three limit states that correspond to the previously mentioned performance levels are employed; Damage Limitation (DL), Significant Damage (SD) and Near Collapse (NC). For each limit state a corresponding chord rotation value is given.

Turkish Earthquake Code (2007):

Turkish Earthquake Code (2007) defines three damage levels based on the ductility capacity and predicted failure mode. Seismic performance of a structure can be determined by considering the distribution of structural damage along the building. For a reinforced concrete column, sectional damage state should be calculated by determining the strain values of concrete fibers and reinforcement. The strain limits are defined as:

The Immediate Occupancy (IO) strain limit is found from Equation 4.11.

$$\left(\varepsilon_{cunconfined}\right)_{IO} = 0.0035;\ (\varepsilon_s)_{IO} = 0.01 \tag{4.11}$$

The Life Safety (LS) strain limit is found from Equation 4.12.

$$\left(\varepsilon_{cconfined}\right)_{LS} = 0.0035 + 0.01\left({}^{\rho_s}/_{\rho_{sm}}\right) \leq 0.0135;\ (\varepsilon_s)_{LS} = 0.04 \tag{4.12}$$

The Collapse Prevention (CP) strain limit is found from Equation 4.13.

$$\left(\varepsilon_{cconfined}\right)_{CP} = 0.004 + 0.014\left({}^{\rho_s}/_{\rho_{sm}}\right) \leq 0.018;\ (\varepsilon_s)_{CP} = 0.06 \tag{4.13}$$

Where;

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

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

ε_s: Steel strain at the critical section

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

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

Since, TEC (2007) assessment procedure requires the information of strain values at the member sections; this procedure is not applicable to the wide-beam building model due to absence of a fiber model for the element section definitions. The wide-beam building model employed a deterioration model rather than a fiber model for members in order to simulate the inherent deformation characteristics of wide-beam column connections. Although, the strain limits values can be converted into rotation values, using the concentrated spring rotations as member rotations would be misleading for the assessment. Yakut and Solmaz (2010) carried out a statistical research study and determined the average performance levels for reinforced concrete columns in terms of drift ratio. The performance limits from different earthquake codes are compared and the results are demonstrated in Table 4.5.

Table 4.5. Statistical Analysis Results Obtained According to Different Seismic Guidelines (Yakut and Solmaz, 2010)

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

The estimated values in the table are found quantitatively by estimating the yield and ultimate displacements in the capacity curve. Although these values cannot be used directly for the fragility analysis of the wide-beam frame structures, they can be useful to compare the estimated drift limits of wide-beam frame building with the average code drifts of reinforced concrete structures.

4.5. Time History Analyses

The wide-beam frame model is analyzed under a set of 100 earthquake excitations and story drifts are recorded within OpenSees. The earthquake set is composed of ground motion data with varying strong ground motion parameters from different earthquakes and stations throughout the world. The ground motion list is given in Appendix, Table A.1. According to the table, M_s stands for surface wave magnitude, ED is epicentral distance, HD is hypocentral distance and CD is the closest distance. V/A is the ratio of peak ground velocity (PGV) to peak ground acceleration (PGA) and generally used to emphasize the local soil conditions. EPA represent the effective peak ground acceleration and found by taking the average of spectral acceleration (Sa) values divided by 2.5 which are taken in period interval of 0.1-0.5 sec. EI is defined as the energy index and calculated from the Equation 4.11.

$$EI = \int_0^4 V_{eq} dT \tag{4.14}$$

Where, V_{eq} is defined as the input energy equivalent velocity. And lastly, the Δt_{eff} is identified as effective duration according to Trifunac and Brady (1976). The strong ground motion data is arranged using proper scale factors in order to maintain a ground motion set with well distributed peak ground velocities (PGV). Hence, smooth fragility curves can be obtained. After consecutive time history analyses, the maximum inter-story drift ratios for each earthquake analysis are stored in an Excel spreadsheet through a TCL procedure. The analysis results are provided in Table 4.6. The time step is set to 0.01 seconds for the analysis yet it is varied for the analysis recording. The analysis handler in OpenSees is able to switch between numerical integration rules such as initial tangent, Broyden and Newton with line search methods. Thus; any possible convergence error during the analysis is overcome. This also caused the analysis handler to continue recording the drift ratio for some of the ground motions after the collapse as well (a spring reaches its ultimate deformation capacity and still continues carrying load). The ground motion entries that show a drift recording after total collapse are colored in red in Table 4.6. These entries are omitted in the fragility study.

Table 4.6. Time history analyses results of the model subjected to ground motion set

EQ. Code	Ground Motion Name	PGV (cm/s)	Inter-story Drift Ratios 1st Story	2nd Story	3rd Story	4th Story	5th Story	Roof Drift	Max Drift
ALK81X02	Alkion	22.72	1.09%	1.18%	1.34%	1.32%	1.01%	1.04%	1.34%
BUC77X01	Bucharest	73.13	4.24%	3.92%	2.28%	1.36%	0.88%	2.28%	4.24%
BUC77X02	Bucharest	70.55	4.68%	4.34%	2.07%	1.38%	0.87%	2.42%	4.68%
CHI99X02	Chi Chi	46.29	2.44%	2.34%	1.80%	1.67%	1.27%	1.66%	2.44%
CHI99X03	Chi Chi	35.38	1.39%	1.54%	1.33%	0.97%	0.69%	1.18%	1.54%
CHI99X05	Chi Chi	43.23	3.52%	2.33%	2.01%	1.36%	0.85%	1.69%	3.52%
CHI99X06	Chi Chi	61.19	1.66%	1.11%	1.01%	0.99%	0.82%	0.82%	1.66%
CHI99X10	Chi Chi	53.07	3.16%	3.37%	2.70%	1.88%	1.17%	2.42%	3.37%
CHI99X11	Chi Chi	64.16	1.99%	1.89%	2.05%	2.02%	1.70%	1.66%	2.05%
CHI99X12	Chi Chi	69.38	2.93%	1.95%	1.90%	1.85%	1.43%	1.48%	2.93%
CHI99Y02	Chi Chi	74.64	5.24%	5.08%	5.76%	6.27%	6.29%	4.17%	6.29%
CHI99Y03	Chi Chi	88.45	5.67%	4.93%	1.69%	1.44%	1.06%	2.67%	5.67%
CHI99Y05	Chi Chi	40.41	1.53%	1.39%	1.38%	1.09%	0.86%	1.08%	1.53%
CHI99Y07	Chi Chi	55.82	2.08%	1.45%	1.18%	0.93%	0.65%	1.05%	2.08%
CHI99Y09	Chi Chi	55.41	4.13%	4.56%	4.16%	3.54%	3.38%	3.93%	4.56%
CHI99Y13	Chi Chi	68.75	5.97%	5.78%	2.51%	1.93%	1.33%	2.78%	5.97%
CLI80X02	Campano	11.27	0.70%	1.01%	1.12%	1.01%	0.70%	0.86%	1.12%
CLI80Y04	Campano	27.46	1.75%	1.56%	1.63%	1.33%	0.92%	1.24%	1.75%
CMD92X02	Cape	48.30	3.04%	2.18%	1.74%	1.97%	1.56%	1.41%	3.04%
CMD92Y02	Cape	89.45	6.24%	4.80%	1.25%	0.56%	0.41%	2.74%	6.24%
COA83X01	Coalinga	10.51	0.36%	0.52%	0.49%	0.45%	0.34%	0.39%	0.52%
DNZ76Y01	Denizli	15.46	0.29%	0.45%	0.46%	0.43%	0.42%	0.35%	0.46%
DZC99X01	Düzce	65.76	3.21%	2.92%	2.33%	1.73%	1.24%	2.13%	3.21%
DZC99X02	Düzce	58.25	3.71%	3.42%	2.59%	2.07%	1.45%	2.22%	3.71%
DZC99Y01	Düzce	86.05	4.33%	4.45%	3.57%	1.55%	0.98%	3.02%	4.45%
DZC99Y02	Düzce	66.92	1.30%	2.18%	2.89%	2.87%	2.32%	2.13%	2.89%
ERZ92X01	Erzincan	87.47	5.70%	5.37%	2.58%	1.77%	1.14%	2.99%	5.70%
ERZ92Y01	Erzincan	92.05	25.5%	4.65%	4.19%	3.22%	2.01%	3.74%	25.53%
HOR83Y01	Horasan	26.02	2.78%	2.85%	2.17%	1.25%	0.77%	1.99%	2.85%
IPV79X02	Imperial Valley	95.89	6.75%	4.83%	1.58%	1.35%	0.95%	2.98%	6.75%
IPV79X03	Imperial Valley	98.52	5.52%	3.60%	2.77%	1.71%	1.01%	2.62%	5.52%
IPV79X08	Imperial Valley	71.77	3.10%	2.56%	2.00%	1.43%	0.94%	1.77%	3.10%
IPV79Y01	Imperial Valley	16.43	0.77%	1.21%	1.29%	1.09%	0.78%	0.98%	1.29%
IPV79Y02	Imperial Valley	49.71	4.88%	2.29%	1.69%	1.42%	1.03%	1.98%	4.88%
IPV79Y08	Imperial Valley	90.45	6.04%	5.28%	4.18%	1.73%	1.09%	3.52%	6.04%
IZM92X01	İzmir	4.34	0.23%	0.27%	0.30%	0.30%	0.25%	0.25%	0.30%
KLM86X01	Kalamata	32.73	1.57%	1.41%	1.53%	1.38%	1.08%	1.17%	1.57%
KLM86X02	Kalamata	31.51	1.36%	1.25%	1.26%	1.31%	1.02%	0.99%	1.36%
KLM86Y02	Kalamata	23.55	0.62%	0.87%	0.95%	0.89%	0.68%	0.73%	0.95%
KOB95X01	Kobe	90.70	2.08%	3.27%	3.35%	3.22%	2.88%	2.72%	3.35%

Table 4.6. Continued

EQ. Code	Ground Motion Name	PGV (cm/s)	Inter-story Drift Ratios 1st Story	2nd Story	3rd Story	4th Story	5th Story	Roof Drift	Max Drift
KOB95X02	Kobe	37.27	2.24%	2.30%	1.87%	1.41%	0.96%	1.63%	2.30%
KOB95X03	Kobe	68.28	3.40%	3.35%	2.69%	1.88%	1.50%	2.30%	3.40%
KOB95Y01	Kobe	75.04	3.24%	2.61%	3.04%	3.26%	2.93%	2.69%	3.26%
KOB95Y02	Kobe	36.60	1.95%	1.88%	1.67%	1.55%	1.22%	1.39%	1.95%
KOB95Y03	Kobe	85.25	3.05%	3.35%	3.22%	2.65%	2.53%	2.92%	3.35%
LAZ84Y02	Lazio Abruzzo	7.90	0.24%	0.31%	0.36%	0.37%	0.27%	0.28%	0.37%
LND92X02	Landers	17.86	1.29%	1.10%	1.07%	0.97%	0.77%	0.86%	1.29%
LND92X04	Landers	29.03	0.97%	1.08%	1.06%	0.99%	0.74%	0.82%	1.08%
LND92Y02	Landers	20.07	1.42%	1.55%	1.46%	1.12%	0.82%	1.18%	1.55%
LND92Y03	Landers	42.71	2.57%	4.16%	4.31%	3.91%	3.44%	3.50%	4.31%
LND92Y04	Landers	50.81	2.19%	1.84%	1.61%	1.36%	1.09%	1.29%	2.19%
LPT89X01	Loma Prieta	55.20	2.13%	2.02%	1.89%	2.00%	1.77%	1.71%	2.13%
LPT89X02	Loma Prieta	41.35	3.34%	2.90%	2.58%	1.81%	1.21%	2.05%	3.34%
LPT89X03	Loma Prieta	13.63	0.59%	0.86%	0.91%	0.89%	0.77%	0.70%	0.91%
LPT89X05	Loma Prieta	36.15	2.02%	2.33%	2.39%	2.04%	2.17%	1.92%	2.39%
LPT89X06	Loma Prieta	32.92	0.81%	1.13%	1.29%	1.25%	0.96%	0.95%	1.29%
LPT89X12	Loma Prieta	62.78	3.78%	3.29%	2.28%	1.43%	0.94%	2.26%	3.78%
LVM80X02	Livermore	9.74	0.37%	0.54%	0.54%	0.51%	0.41%	0.44%	0.54%
MAR99X01	Marmara	79.60	7.50%	3.93%	1.88%	1.14%	0.82%	2.91%	7.50%
MAR99X03	Marmara	45.59	1.56%	1.57%	1.48%	1.29%	0.98%	1.16%	1.57%
MAR99X04	Marmara	60.59	3.20%	2.83%	2.71%	1.74%	1.04%	2.07%	3.20%
MAR99X09	Marmara	8.34	0.20%	0.30%	0.34%	0.37%	0.30%	0.27%	0.37%
MAR99Y01	Marmara	84.70	4.96%	4.87%	3.88%	2.05%	1.22%	3.41%	4.96%
MAR99Y02	Marmara	54.28	1.79%	1.90%	1.58%	1.35%	1.04%	1.35%	1.90%
MAR99Y03	Marmara	34.72	1.04%	0.88%	1.00%	0.88%	0.57%	0.71%	1.04%
MAR99Y05	Marmara	79.80	3.07%	2.11%	1.97%	1.63%	1.13%	1.68%	3.07%
MGH84X01	Morgan Hill	4.99	0.31%	0.39%	0.46%	0.47%	0.40%	0.38%	0.47%
MGH84Y03	Morgan Hill	5.76	0.29%	0.27%	0.30%	0.31%	0.26%	0.24%	0.31%
MGH84Y04	Morgan Hill	80.79	2.12%	2.26%	2.38%	2.62%	2.32%	1.87%	2.62%
MNJ90X02	Manjil	1.09	0.08%	0.12%	0.13%	0.13%	0.10%	0.11%	0.13%
MNJ90Y01	Manjil	55.44	5.96%	6.10%	4.29%	1.74%	1.02%	3.91%	6.10%
MNJ90Y02	Manjil	1.24	0.06%	0.12%	0.13%	0.12%	0.10%	0.10%	0.13%
MTN79X01	Montenegro	38.82	1.26%	1.44%	1.22%	1.77%	1.90%	1.06%	1.90%
MTN79Y01	Montenegro	25.31	0.66%	0.73%	0.86%	1.09%	1.01%	0.62%	1.09%
MTN79Y02	Montenegro	47.08	2.57%	3.01%	2.67%	1.88%	1.29%	2.24%	3.01%
NRD94X05	Northridge	51.11	1.86%	1.58%	1.62%	1.73%	1.69%	1.21%	1.86%
NRD94X06	Northridge	80.33	4.60%	4.66%	4.23%	3.28%	2.45%	3.80%	4.66%
NRD94X07	Northridge	96.52	5.27%	5.66%	5.43%	3.19%	2.02%	4.28%	5.66%
NRD94X08	Northridge	14.88	0.33%	0.50%	0.56%	0.55%	0.42%	0.44%	0.56%
NRD94X09	Northridge	12.70	0.48%	0.69%	0.70%	0.55%	0.40%	0.54%	0.70%
NRD94X10	Northridge	24.91	2.82%	2.23%	1.48%	1.30%	1.01%	1.43%	2.82%
NRD94X12	Northridge	52.56	2.80%	3.06%	2.69%	2.93%	3.10%	2.38%	3.10%

Table 4.6. Continued

EQ. Code	Ground Motion Name	PGV (cm/s)	Inter-story Drift Ratios 1st Story	2nd Story	3rd Story	4th Story	5th Story	Roof Drift	Max Drift
NRD94X13	Northridge	94.72	5.10%	4.84%	2.28%	2.50%	2.16%	2.68%	5.10%
NRD94X15	Northridge	77.18	3.29%	4.10%	2.86%	2.41%	1.95%	2.89%	4.10%
NRD94X19	Northridge	84.85	2.29%	2.38%	2.36%	2.25%	1.79%	1.88%	2.38%
NRD94Y05	Northridge	44.56	1.99%	1.64%	1.66%	1.83%	1.61%	1.34%	1.99%
NRD94Y13	Northridge	74.84	2.07%	1.89%	1.57%	1.26%	1.07%	1.36%	2.07%
NRD94Y14	Northridge	30.95	0.92%	1.31%	1.16%	0.97%	0.79%	0.94%	1.31%
NRD94Y15	Northridge	97.49	5.98%	5.41%	2.05%	1.81%	1.73%	2.98%	5.98%
NRD94Y19	Northridge	76.60	4.25%	2.04%	1.84%	1.78%	1.38%	1.81%	4.25%
NRD94Y21	Northridge	61.48	4.94%	4.96%	4.84%	2.82%	1.83%	3.67%	4.96%
NRD94Y22	Northridge	99.28	5.65%	5.89%	4.41%	2.58%	1.83%	4.10%	5.89%
SFE71X01	San Fernando	29.80	2.23%	1.85%	1.58%	1.31%	1.01%	1.35%	2.23%
TBS78X02	Tabas	90.23	5.67%	5.09%	3.47%	1.93%	1.56%	3.61%	5.67%
TBS78Y02	Tabas	80.53	7.27%	4.70%	3.42%	1.90%	1.77%	3.55%	7.27%
VRN90X02	Vrancea	6.45	0.18%	0.25%	0.26%	0.23%	0.18%	0.20%	0.26%
VRN90Y02	Vrancea	2.08	0.18%	0.27%	0.33%	0.29%	0.20%	0.24%	0.33%
WHN87X01	Whittier Narrows	21.72	0.50%	0.54%	0.58%	0.47%	0.44%	0.42%	0.58%
WHN87X02	Whittier Narrows	19.16	0.74%	1.11%	1.04%	0.79%	0.65%	0.75%	1.11%
WHN87Y01	Whittier Narrows	16.95	0.45%	0.44%	0.48%	0.58%	0.51%	0.33%	0.58%

Ground motion records have already been processed and necessary corrections were made by Erberik (2008) in a vulnerability study on concrete structures. 100 ground motion records with evenly varied PGA values were selected out of 292 earthquake records. The maximum drift values are plotted against each ground motion parameter; peak ground acceleration (PGA), peak ground velocity (PGV), spectral acceleration (S_a), spectral velocity (S_v) and spectral displacement (S_d) to produce power fit equations, which are employed in the fragility study. Peak ground velocity (PGV) gives the best trend among the power fit curves with the highest R^2 value. Spectral parameters S_a, S_v and S_d have the second highest R^2 value of 0.6677 by possessing a mediocre fit. Peak ground acceleration produces the least successful power fit curve with the lowest R^2 value and therefore presents a relatively poor data set for the fragility analysis.

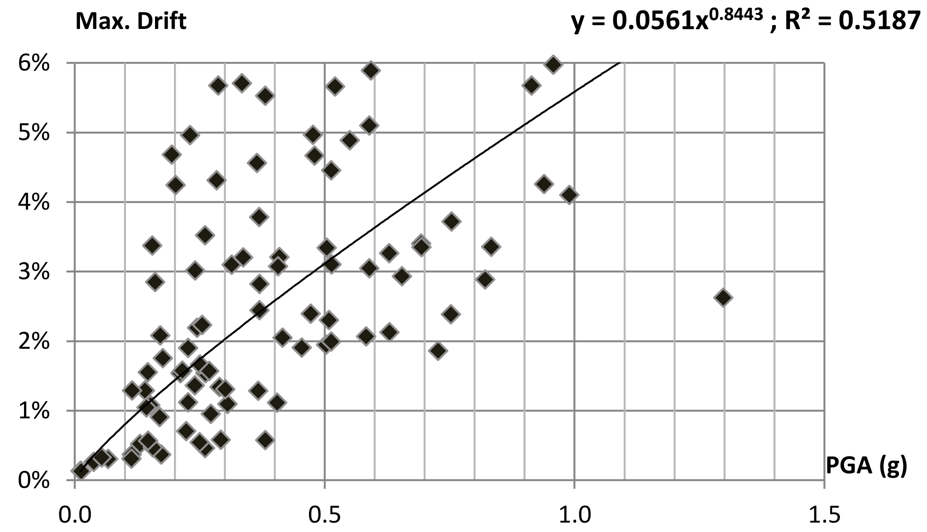

Figure 4.12. Development of power law equation with respect to PGA

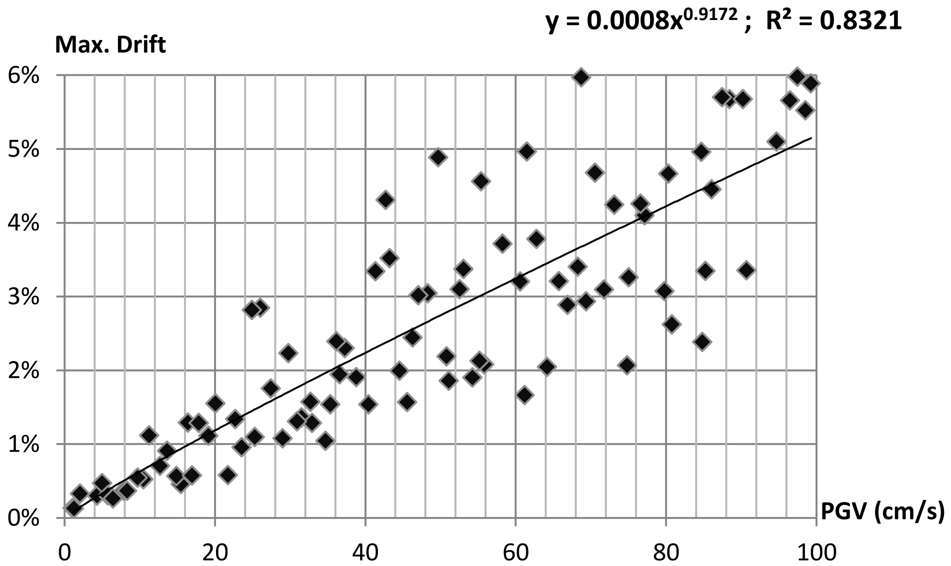

Figure 4.13. Development of power law equation with respect to PGV

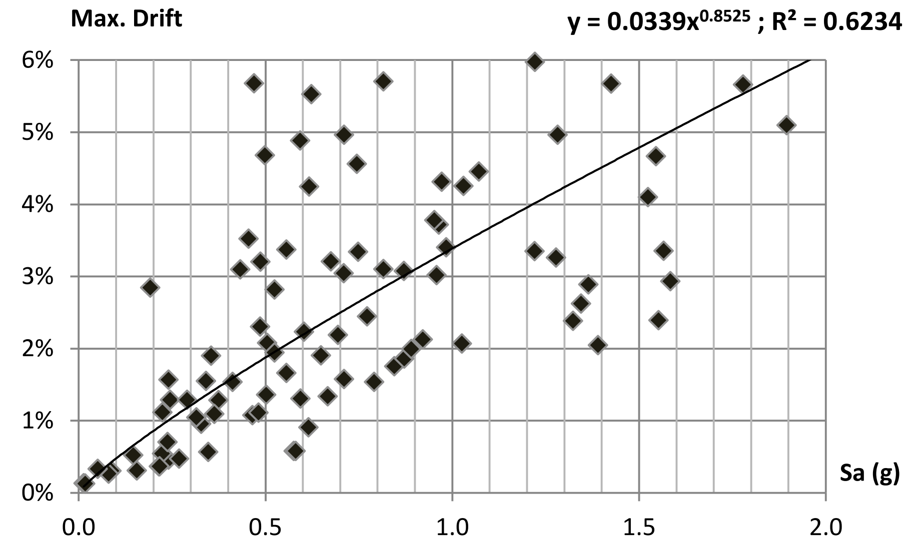

Figure 4.14. Development of power law equation with respect to S_a

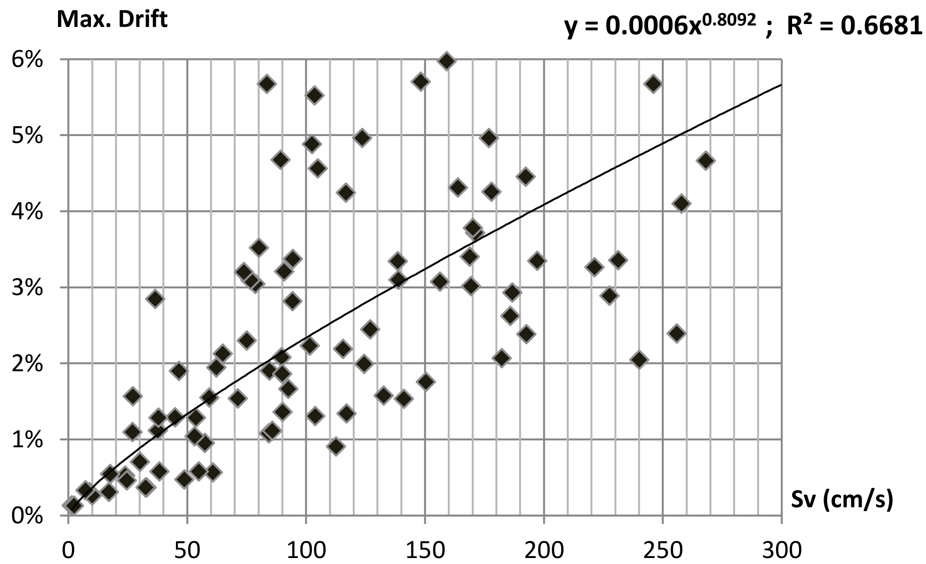

Figure 4.15. Development of power law equation with respect to S_v

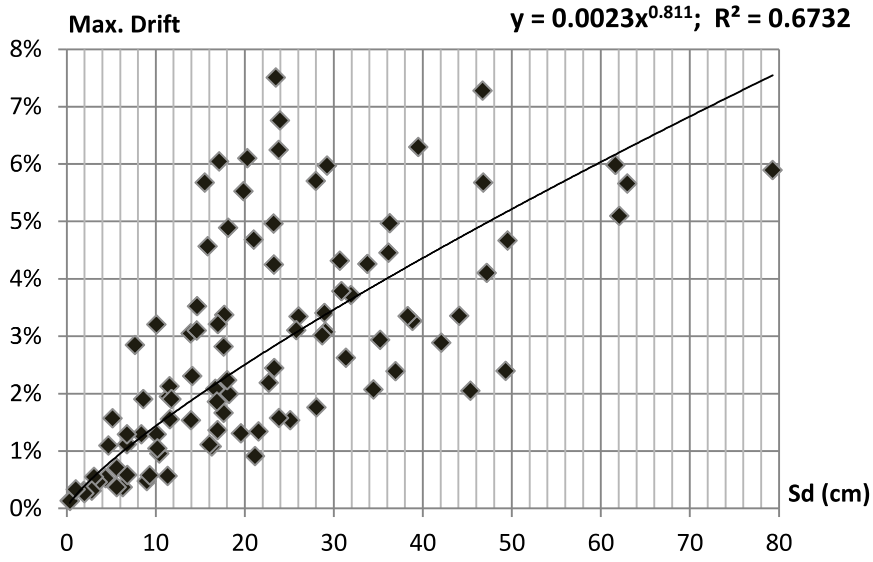

Figure 4.16. Development of power law equation with respect to S_d

4.6. Development of Fragility Curves

A fragility curve represents the relationship between the ground motion intensities and the probability of a certain damage level. These damage levels have been previously defined as Immediate Occupancy (IO = 0.45%), Life Safety (LS = 1.15%) and Collapse Prevention (CP = 2.45%) in terms of inter-story drift ratios. The earthquake response is assumed to follow a lognormal distribution and the probability of this response reaching or exceeding a certain limit state is obtained by the fragility equation given below.

$$P(LS/S_a) = 1 - \left(\frac{\ln \eta_C - \ln \eta_{D/S_a}}{\sqrt{\beta_{D/S_a}^2 + \beta_C^2 + \beta_M^2}} \right) \tag{4.15}$$

Where;

η_C : Median drift capacity for a limit state

η_{D/S_a} : Median drift demand given the ground motion intensity S_a

β_{D/S_a} : Standard deviation of the natural logarithm of drift demand

β_C : Standard deviation of the natural logarithm of drift capacity

β_M : The uncertainty associated in the analytical modelling

Median drift capacity for each limit state were found previously as η_{IO}= 0.45%, η_{CLS}= 1.15% and η_{CP}= 2.45%. Median drift demands are calculated from the power law equation found in Figure 4.12 and Figure 4.13. Standard deviation of the natural logarithm of drift demand β_{D/S_a} is calculated from the following equation.

$$\beta_{D/S_a} = \sqrt{\ln(1+s^2)}\,;\; s^2 = \frac{\sum[\ln Y_i - \ln Y_p]}{n-2} \tag{4.16}$$

Where, s^2 is defined as the square of the standard error. On the other hand, Y_i and Y_p are the observed demand drift and power-law predicted demand drift, respectively for a given vulnerability factor. The fragility curves are developed for different earthquake fragility factors such as PGA, PGV, S_a, S_v and S_d.

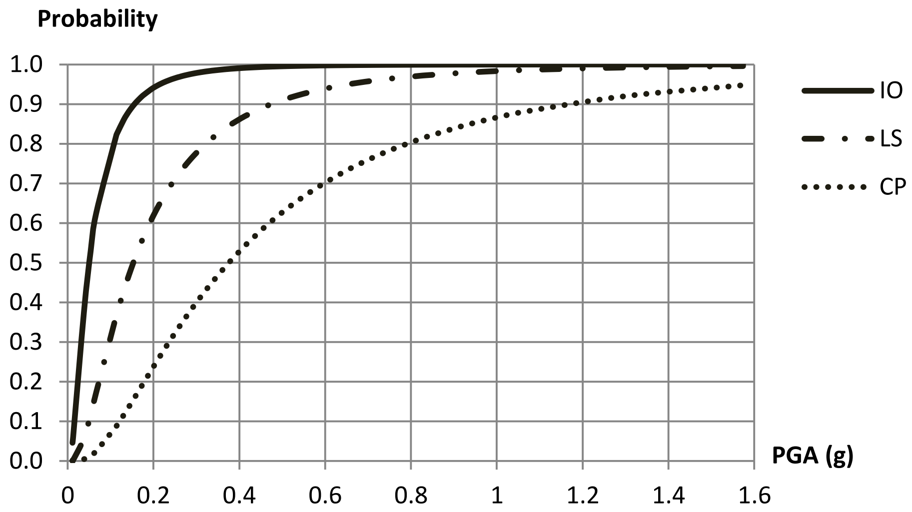

Figure 4.17. Fragility curve of the wide beam model with respect to PGA

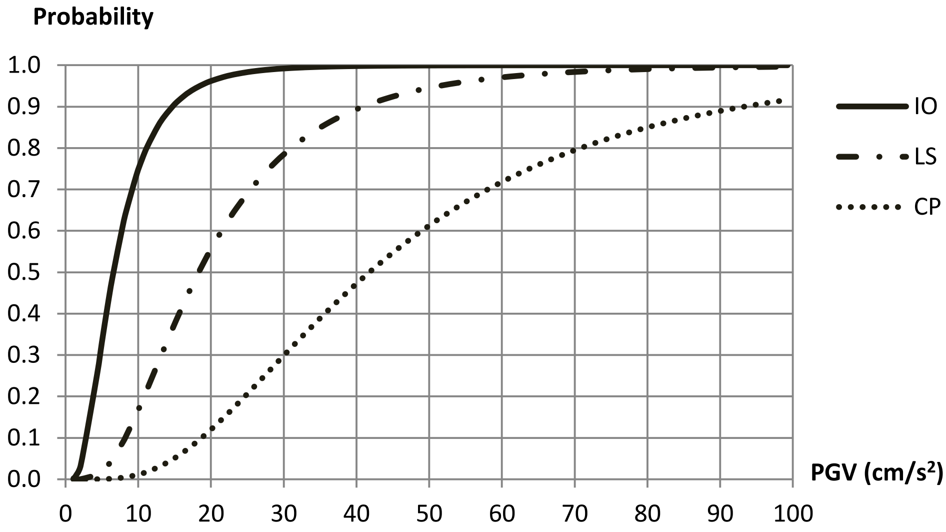

Figure 4.18. Fragility curve of the wide beam model with respect to PGV

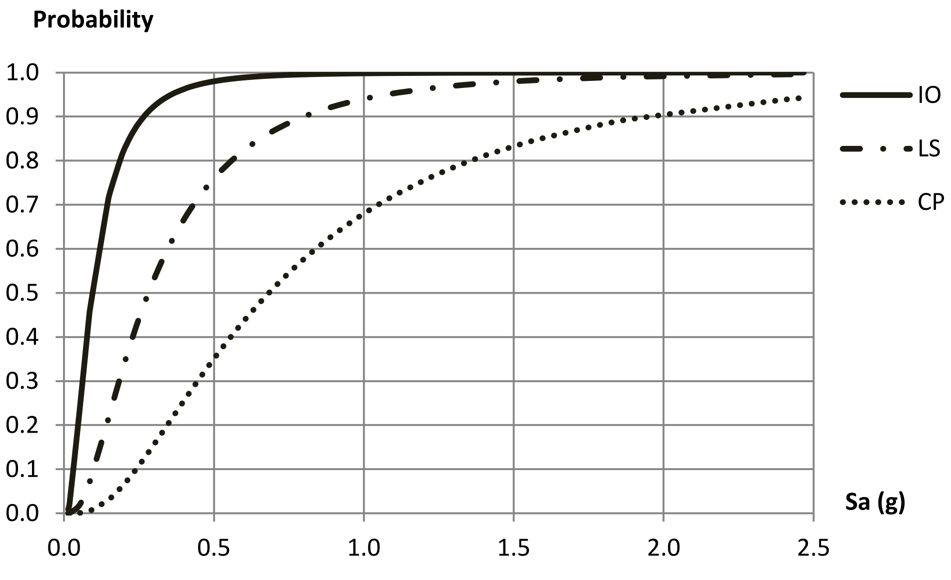

Figure 4.19. Fragility curve of the wide beam model with respect to S_a

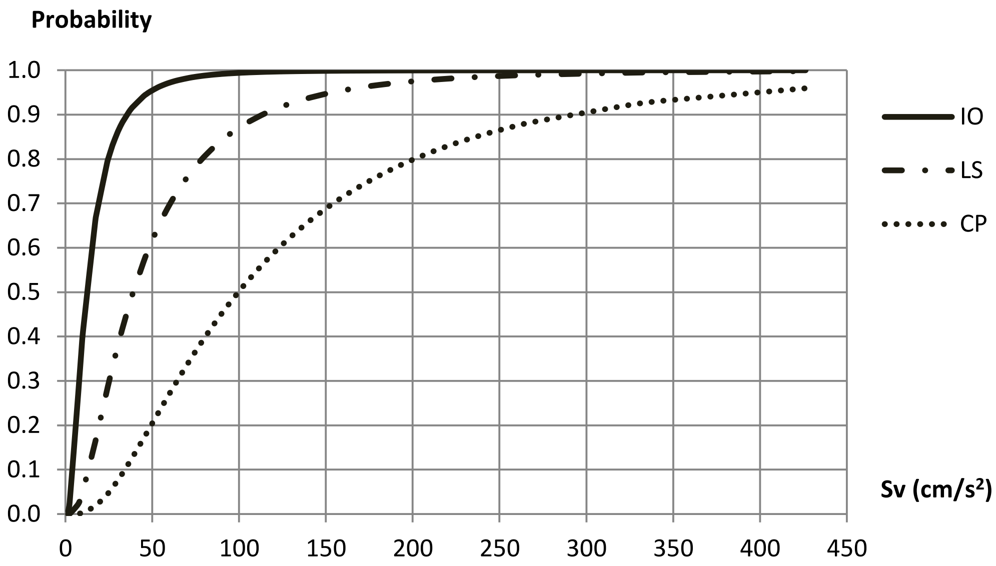

Figure 4.20. Fragility curve of the wide beam model with respect to S_v

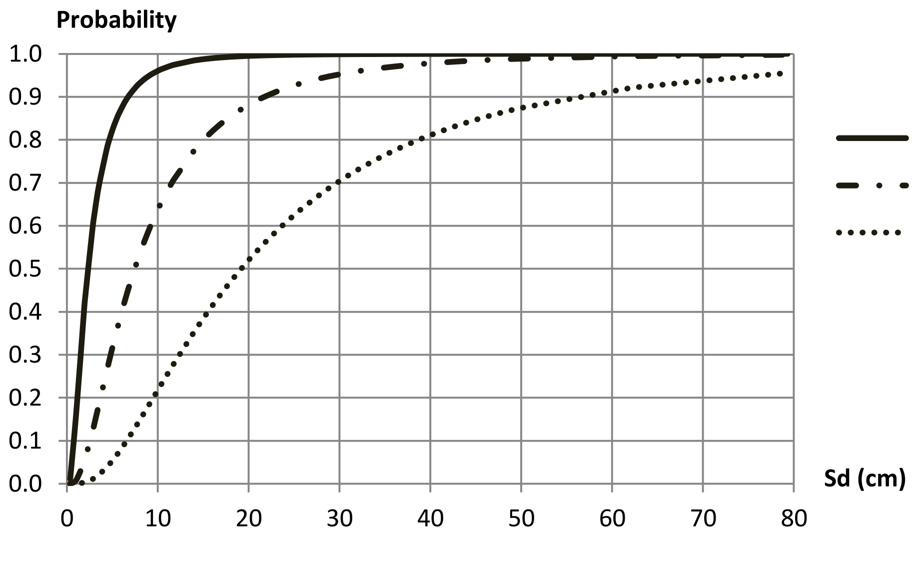

Figure 4.21. Fragility curve of the wide beam model with respect to S_d

4.7. Performance Evaluation and Comparison with Other Studies

The seismic performance of the considered wide-beam frame building model is evaluated through the fragility analysis carried out in Section 4.6. This building model with selected geometry and material parameters is a very typical wide beam structure widespread in Turkey. Its fragility curve would be an indicator for earthquake performance when compared with other fragility studies on similar size buildings which are also considered as typical construction practice in high seismicity regions. In the following paragraphs, the fragility curve set of the selected wide beam building model is matched with fragility curve sets of other types of buildings in the literature. Although the compared buildings has its own limit states, the comparison would still make sense; since both structures that are compared to each other are measured in terms of probability of passing its own performance level. Namely, a rational comparison does not necessarily require having the same deformation limits. On the contrary, these values should be specific to the building or to the construction type for fair comparison.

First, the comparison is made with the vulnerability of a 6-story wide-beam frame structure studied by Lopez-Almansa et. al. (2013). Then, several other fragility studies are compared in order to quantitatively measure the vulnerability of wide-beam frame structures against other construction types. Among the buildings compared, a 5-story reinforced concrete frame building studied by Ay and Erberik (2008), a mid-rise infilled reinforced concrete building studied by Mosalam et. al. (1997), a 5-story flat slab building studied by Erberik and Elnashai (2004) and a 5-story flat slab reinforced concrete building studied by Hueste and Bai (2006) are reviewed. All these buildings are considered as prevalent construction practice and they have similar building heights.

In all comparisons, the fragility curves that belong to the wide-beam frame building are shown in color red. The drift limits of the reviewed vulnerability studies are also provided in Table 4.7.

Table 4.7. Comparison of performance limit states of different studies (in drift ratio)

Structure Type	Method	IO (%)	LS (%)	CP (%)
Modelled wide-beam building frame	Quantitative	0.45	1.15	2.45
6-story wide-beam building by Lopez-Almansa et. al. (2013)	Quantitative	0.21	0.48	0.65
5-story reinforced concrete frame building studied by Ay and Erberik (2008)	Quantitative	0.46	1.28	3.47
Mid-rise infilled reinforced concrete building studied by Mosalam et. al. (1997)	MMI*	0.5	1.0	1.5
5-story flat slab building studied by Erberik and Elnashai (2004)**	Quantitative	0.1-1.0	1.0-2.0	2.0-3.5
5-story flat slab reinforced concrete building studied by Hueste and Bai (2006)	FEMA 356	1.0	2.0	2.9

*Modified Marcali Index, **Erberik (2004) used 4-level limit states

The vulnerability of the selected wide beam frame building is first compared with the results of the seismic vulnerability analysis conducted by Lopez-Almansa et. al. (2013). A numerical study of the seismic vulnerability of RC buildings with one-way wide-beam slabs located in moderate seismicity regions of Spain was carried out in that study. Two 3-story and four 6-story buildings were selected to represent the vast majority of the existing buildings. The cooperation of the infill walls was accounted for; accordingly, for each building, three wall densities were considered: no walls, low density and high density. Vulnerability was investigated by code-type analyses, by push-over analyses and by nonlinear dynamic analyses. The torsional effects were not considered in the analyses. However, the vulnerability investigations were not demonstrated in terms of fragility curves; therefore, a suitable comparison was held in terms of damage state probability. The following table shows damage levels of the buildings with varied number of stories under certain earthquakes (Building 3-5: three-story buildings, Building 6-5: six-story buildings).

Table 4.8. Damage level of buildings 3 – 5 and 6 – 5 (Lopez-Almansa et. al., 2013)

Bldg.	Dir.	Wall density	Dynamic analyses Friuli (11/09/76) (NS)	Kalamata (13/09/86) (NS)	Izmit (17/08/99) (NS)	Izmit (17/08/99) (EW)	Duzce (12/11/99) (EW)	Push -over	Code -type
3 – 5 – ■	Wide beams (*x*)	None	HD	HD	HD	HD	HD	ED	HD
		Low	HD	HD	SD	ND	HD	ED	ED
		High	MD	MD	ND	ND	MD	MD	ND
	Trans. (*y*)	None	HD	HD	HD	HD	HD	ED	HD
		Low	HD	HD	MD	SD	HD	ED	ED
		High	MD	MD	SD	ND	MD	MD	MD
6 – 5 – ■	Wide beams (*x*)	None	HD	HD	HD	HD	HD	HD	HD
		Low	HD	HD	HD	HD	HD	HD	HD
		High	HD	HD	ND	ND	HD	HD	ED
	Trans. (*y*)	None	HD	HD	HD	HD	HD	HD	HD
		Low	HD	HD	HD	HD	HD	HD	HD
		High	HD	HD	ND	ND	HD	HD	ED

Peak ground acceleration (PGA) values are gathered for each earthquake excitation in Table 4.8 and the corresponding damage conditions are found from Figure 4.17. The damages states are then compared with the damage levels for 6-story low wall density wide beam frames in x direction found by Lopez-Almansa et. al (2013). The performance states of the selected wide beam building under the given earthquakes are displayed in Table 4.9 for comparison.

Table 4.9. Fragility of the wide beam building under corresponding PGA values

EQ Name:	Friuli(NS)	Kalamata(NS)	Izmit(NS)	Izmit(EW)	Duzce(EW)
Probability of Heavy Damage	%99	%85	%85	%75	%90

Some of the earthquakes listed in Table 4.9 are not included in the original fragility analysis. Therefore, the probability of occurring a damage state is found for each corresponding PGA value. The comparison shows that heavy damage is quite possible to occur in all earthquakes according to both the fragility analysis carried by Lopez-Almansa et. al. (2013) and the fragility analysis in this thesis.

Ay and Erberik (2008) investigated the vulnerability of Turkish low-rise and mid-rise reinforced concrete frame structures. These structures constitute approximately 75% of the total building stock in Turkey. Fragility curves are obtained for 3, 5, 7, and 9–story reinforced concrete moment resisting frame structures. The comparison is made for 5-story building with typical subclass.

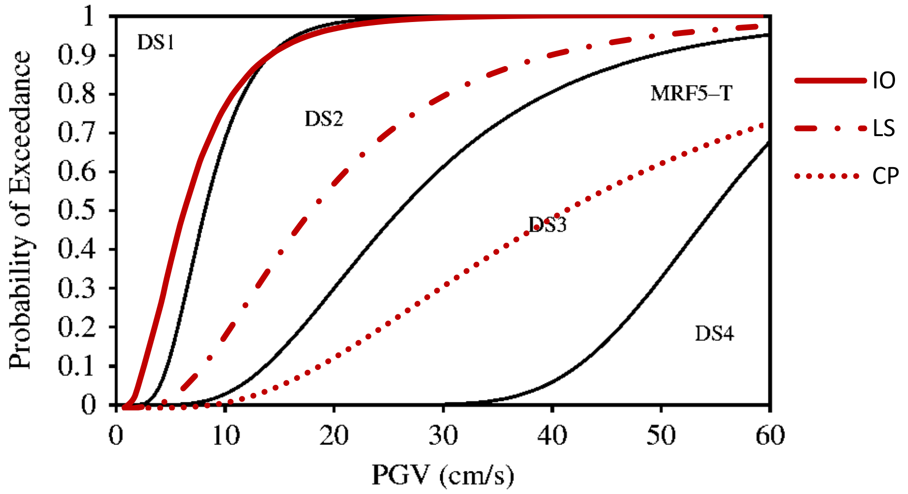

Figure 4.22. Comparison of fragility curves with 5-story RC frame building

The red lines plotted on the fragility curve set of Ay and Erberik (2008) represent the wide beam frame building. Although the fragility lines for both structures have close trend in the immediate occupancy (IO) performance level; the wide-beam building is more vulnerable at other performance levels. The compared reinforced concrete frame structure has typical subclass for concrete material which is inferior to the concrete material used in wide beam structures. Yet, the both material classes represent the common construction practice in Turkey in their building categories. Thus, it was more convenient to compare with the typical subclass building rather than the superior class building given in the fragility study of Ay and Erberik (2008).

Mosalam et al. (1997) developed fragility curves for low-rise and mid-rise Lightly Reinforced Concrete (LRC) frames with masonry infill walls. The researchers employed a different computation method, the Dynamic Plastic Hinge Method (DPHM), which is a simplified method to minimize the effort and the expense involved in determination of the structural response. DPHM reduces MDOF structure to an equivalent SDOF oscillator with equivalent nonlinear properties. In the implementation of DPHM, properties of equivalent SDOF are obtained by using the Adaptive Pushover Analysis. It was concluded in the vulnerability study that LRC frames with masonry infill walls are relatively more vulnerable when compared to conventional RC frames. The comparison with the wide-beam frame structure will be conducted by matching the fragility curves of both structures and determine whether the considered wide-beam building is more vulnerable than the similar size LRC frame with infill walls.

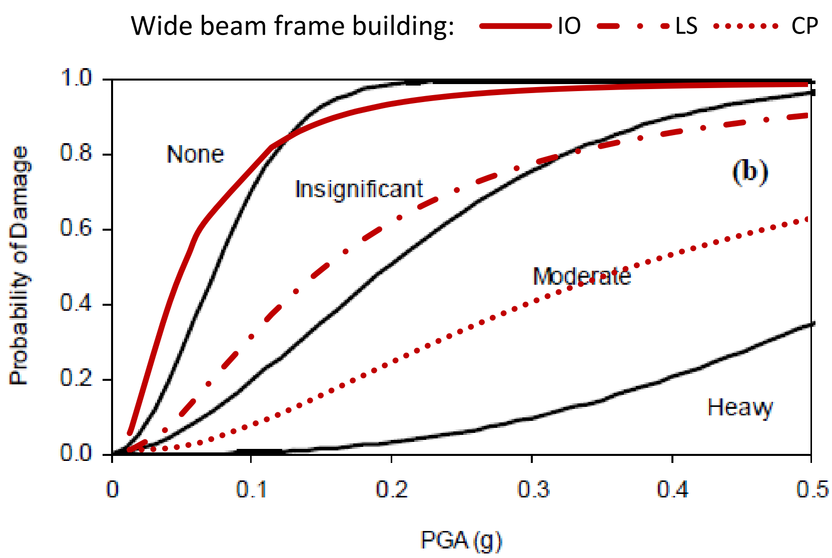

Figure 4.23. Comparison of fragility curves with low-rise infilled beam column RC frame system (Mosalam et al., 1997)

As can be observed from the matching, the both structures show close trend in the immediate occupancy (IO) and life safety (LS) limit states. Yet, the wide-beam frame structure is more vulnerable for the collapse prevention (CP) performance level.

Erberik and Elnashai (2004) carried out a set of fragility analyses for a typical flat slab structure to be implemented in FEMA's HAZUS methodology. The analyses were conducted for a typical five-story three-bay flat slab building which can be considered as mid-rise construction. The typical story height was 2.8m and bay width was 6m. The building was designed according to ACI 318-99 (ACI, 1999) and the seismic design was carried out according to FEMA 368 (2000).

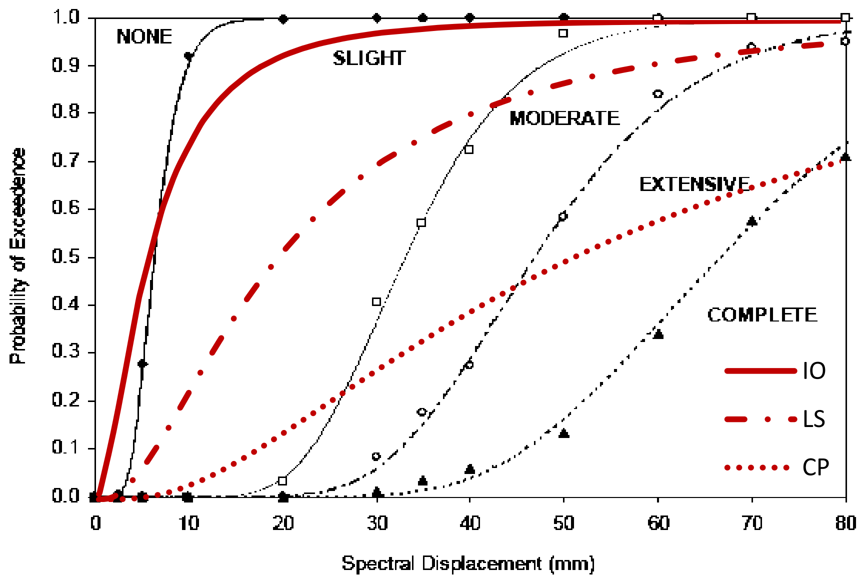

Figure 4.24. Comparison of fragility curves with five-story flat slab frame system (Erberik and Elnashai, 2004)

Comparison of fragility curves with the flat slab structure developed by Erberik and Elnashai (2004) indicated that the wide beam frame building is more vulnerable than the flat-slab frames for every damage state. The vulnerability of the wide-beam structure at immediate occupancy (IO) target performance is almost as high as the flat-slab structure studied by Erberik and Elnashai (2004) at no damage target performance level.

Hueste and Bai (2006) used both the code-defined performance levels and the quantitative limits by Wen et. al. (2003) for his vulnerability analysis whose fragility curve set will later be compared with the wide-beam building's fragility curve set. The seismic performance of a five-story reinforced concrete (RC) flat-slab building representative of 1980s construction in the Central United States was evaluated using nonlinear analysis with synthetic ground motion records and the FEMA 356 (2000) seismic performance criteria. Since, the building geometry and material properties are very similar to the selected wide-beam building; the comparison of their fragility curve sets would indicate the level of vulnerability for use of wide beam frame systems in earthquake prone regions. Both fragility curves are shown in Figure 4.25.

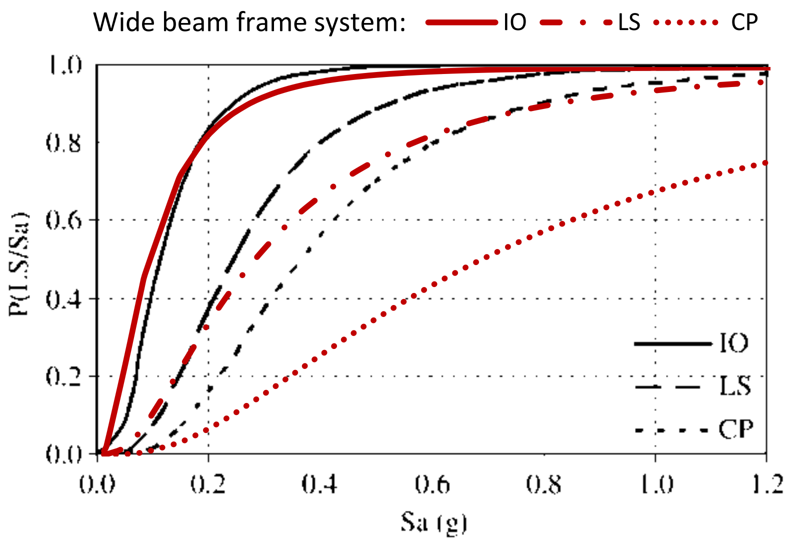

Figure 4.25. Comparison of fragility curves with five-story flat slab frame system (Hueste and Bai, 2008)

For immediate occupancy (IO) performance level, both frames demonstrated poor performance with very brittle behavior. The reduced initial stiffness of wide beam connections possibly caused early yielding of the members in the frame by fostering very similar trend with the flat slab building. The flat slab building is more vulnerable than the wide-beam frame structure for both the life safety (LS) and the collapse prevention (CP) target performance levels. This may be attributed to ductile behavior of the wide-beam frame systems and prolonged capacity reach under seismic excitation.

Comparing the vulnerability of the wide-beam frame structure with other construction types gives an insight about the level of vulnerability of this type of structures. Thereby, a decision making process is possible between the feasibility and vulnerability for different construction types during the design phase of the buildings. Several outcomes can be drawn from the fragility comparisons of similar height building constructions with typical construction practice in their own categories: The wide beam frame structure is by far more vulnerable than the conventional reinforced concrete frames according to the fragility studies by Ay and Erberik (2009) and Mosalam et al. (1997). Although the comparison with the flat slab structure studied by Erberik and Elnashai (2004) shows that the considered wide-beam structure is more vulnerable; the comparison with the other similar height flat slab structure studied by Hueste and Bai (2006) yielded a contradictory result.

CHAPTER 5

SUMMARY, CONCLUSIONS AND FUTURE STUDIES

5.1. Summary

Wide beam infill joist block frame structures constitute a sizeable portion of current construction practice in Turkey. Their ease of construction, cost efficiency and architectural flexibility make them favorable for low-rise and mid-rise building construction. This type of structure is known as “banded floor” in the US, “wide beam frame” in Europe and “asmolen” in Turkey, being adopted widely in earthquake prone countries as well. Yet, wide beam systems demonstrate inadequate performance under seismic excitations according to past studies (e.g. Wight 1994, Climant 2006, Kulkarni 2010 and Dönmez 2013). Due to the shallow depth, wide-beams have lower stiffness values causing the structures to have longer natural periods (Dönmez 2013). It is reported that if special precautions are not taken, the development of beam flexural bars outside the column core section are problematic. Premature failures before reaching the moment capacity could prevail. Therefore; the use of wide beam systems in earthquake regions should be restricted by earthquake codes through accommodating more detailed provisions.

Turkish earthquake code has gone into provisional modifications regarding use of wide beam systems. In 1967, it was prohibited in high seismicity regions, yet a few years later, in 1975, its use was permitted if structural walls are constructed. In 1997, this restriction was lifted. Currently, TEC (2007) allows the use of wide beam systems, as long as a high ductility frame is used with some limitations on sectional dimensions. However, as indicated in the thesis research, the investigated wide-beam frame structure of common construction practice in Turkey (typical geometry and material properties commonly used in Turkey are selected) demonstrated highly vulnerable behavior under seismic excitations when compared to similar height conventional reinforced concrete frame although it satisfies the seismic design requirements of TEC (2007). This shows that, this type of construction should not be considered as conventional reinforced concrete frame construction and further limitations on wide-beam column connections are required to maintain a fair seismic performance. Considering that there is very limited research study on wide-beam frame structures in Turkey, a provisional revision in the seismic code would require much more extensive research. This thesis aimed to produce a seismic performance assessment on wide-beam frame structures in this perspective.

In the first part of the research, a comprehensive literature review on seismic behavior of wide-beam column connection as well as the OpenSees framework and the input language TCL was conducted. Through the computer simulations using OpenSees, the inherent characteristics of the wide-beam connections are attempted to be integrated into the model. For this purpose, different experiment setups in the literature are modelled in OpenSees and the inherent connection behavior is simulated through a deterioration model developed by Ibarra and Krawinkler (2005).

The hysteresis loops in past studies are used in order to calibrate the hysteretic parameters of Modified Ibarra-Krawinkler Hysteresis Model. A calibration procedure that can be generalized to wide-beam connections was developed within this part of the research. A material procedure coded in OpenSees and this material is assigned to zero-length rotational spring elements. In this way, all the nonlinearity is lumped in these springs.

In the final part of the research, the earthquake performance of a full-scale uniform wide beam building is simulated in OpenSees with a 2D frame model. The geometry and material properties are selected as in typical application of wide beam systems in Turkey. Dönmez (2013) carried out an extensive research on post-earthquake investigation of wide beam buildings after Van earthquake and revealed the seismic risks caused by structural deficiencies of wide-beam frame structures. He also pointed out the prevalent construction practice of wide-beam systems in Turkey by investigating the commonly used material and geometric characteristics. After properly selecting the building parameters, the conformity with TEC 2007 is maintained by verifying that the drift limits are not passed during equivalent lateral load analysis. A pushover analysis is held in order to define the performance limits. Since the limit state values are very influential in fragility spectra especially for highly vulnerable buildings, they needed to be defined realistically. The structural behavior that includes hinging sequence, ultimate building capacity and first yield determines the limit values.

After the limit deformation values are defined, the selected wide beam building is analyzed under a set of earthquakes and maximum inter-story drifts are recorded during time history analysis (THA). The maximum drift values are plotted against an earthquake intensity parameter (PGA, PGV, S_a, S_v and S_d) to produce a corresponding power law equation. A set of fragility spectra is produced for different earthquake vulnerability parameters so that a suitable comparison can be made with other fragility analyses belonging to different types of buildings. In some studies, spectral displacement (S_d) was chosen as the earthquake vulnerability parameter; whereas in some other fragility analysis PGA was the vulnerability parameter.

The comparison of fragility curves with other building types such as flat slab and RC moment frame shows the level of vulnerability of wide-beam frame building in seismic regions. Although the compared buildings have different geometric and material properties, they represent the common construction practice in their categories. This can be a basis for comparison.

5.2. Conclusions

This thesis study puts forward the following conclusions:

- Research on vulnerability of wide beam structures is very limited. However, there is a considerable number of existing wide beam buildings and a widespread construction practice of wide beam frame structures which are entitled as reinforced concrete frame.
- This study shows that; it is important to simulate the inherent characteristics of specific construction types such as wide beam frame structures in order to estimate their seismic vulnerabilities in a realistic manner. Treating this type of

systems as if they behave like conventional RC moment frames would be a misleading assumption since; these inherent characteristics significantly increase the seismic vulnerability of the wide-beam frame structure according to the fragility study in this thesis.

- A calibration study with the experimental research studies in the literature can be very useful to simulate the hysteresis behavior of wide-beam column connections realistically.
- Wide beam infill block frame structures in Turkey seem to be seriously vulnerable to seismic action although they conform to the up-to-date earthquake design requirements specified in Turkish earthquake code. The fragility curves of the wide-beam structure fall behind the fragility curves of similar size conventional RC moment frames studied by several other researchers for same target performance level. This is due to their low lateral stiffness, causing large inter-story drifts and therefore significant damage at the beam column connections. These structures should therefore be braced or constructed with RC shear walls.

5.3. Future Studies

The thesis research contains many idealizations and simplifications which can be referred in future studies given as follows:

- A regular building with similar and symmetrical bare frames is selected as model building in the research in order to carry out 2D computer analysis. (Even 2D analysis takes very significant time for a hundred of consecutive time history analyses). However, this is not always the case in reality. Unfinished or skew frames may sometimes exist and sometimes a column connects with the joist rather than the wide beam by making it more vulnerable. It is quite difficult to model these structures when there are such irregularities. Hence, a future challenge can be focused on 3D modelling of a complex wide beam structure.
- The thesis research occupied a hysteresis model for the connections which was calibrated based on existing experimental studies of wide beam connections.

Thereby, additional lateral drift caused by torsional stresses occurring in a single connection due to varied anchorage conditions of wide beam reinforcements is somewhat reflected. However a complete 3D finite element model with certain irregularities would successfully investigate the torsional stresses in the building.

- The effect of RC shear walls and braces on performance of wide beam buildings can be investigated in future studies.

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APPENDIX A

A.1. Ground Motion Data Table

The table is displayed in the next pages.

Table A.1.Ground motion data list for Time History Analysis (THA)

Country	**Date**	**Location**	**Site Geology**	**Comp**	**M_s**	**M_w**	**ED (km)**	**HD (km)**	**CD (km)**	**Scale**	**PGA (g)**	**PGV (cm/s)**	**V/A (s)**	**EPA (g)**	**EI**	**Δt_{eff} (s)**
ALK81X02	Alkion	Xilokastro, OTE Building	Alluvium	L	6.7	_	19	_	_	1	0.289	22.72	0.080	0.263	68.33	15.40
BUC77X01	Bucharest	Bucharest, BRI	Alluvium	NS	7.1	_	161	_	_	1	0.202	73.13	0.370	0.123	142.58	6.85
BUC77X02	Bucharest	Vrancioaia	Rock	NS	7.1	_	4	_	_	1	0.194	70.55	0.370	0.107	141.77	8.11
CHI99X02	Chi Chi	TCU074, Nantou Nanguang School	Class D (UBC97)	360	7.6	7.6	_	_	14	1	0.370	46.29	0.128	0.312	116.15	21.19
CHI99X03	Chi Chi	TCU075, Nantou Tsaotun School	Class D (UBC97)	360	7.6	7.6	_	_	3.4	1	0.262	35.38	0.138	0.197	94.22	32.42
CHI99X05	Chi Chi	TCU122, Changhua Ershui School	Class D (UBC97)	360	7.6	7.6	_	_	9.2	1	0.261	43.23	0.169	0.215	101.09	30.71
CHI99X06	Chi Chi	TCU049	USGS (C)	NS	7.6	7.6	_	_	4.5	1	0.251	61.19	0.249	0.223	100.38	22.72
CHI99X10	Chi Chi	TCU109	USGS (C)	NS	7.6	7.6	_	_	13	1	0.155	53.07	0.349	0.140	175.25	31.24
CHI99X11	Chi Chi	TCU076	Class D (UBC97)	NS	7.6	7.6	_	_	3.2	1	0.416	64.16	0.157	0.337	133.55	28.13
CHI99X12	Chi Chi	TCU071	Class D (UBC97)	NS	7.6	7.6	_	_	4.9	1	0.655	69.38	0.108	0.601	122.36	23.73
CHI99Y02	Chi Chi	TCU074, Nantou Nanguang School	Class D (UBC97)	90	7.6	7.6	_	_	14	1	0.595	74.64	0.128	0.433	202.74	12.61
CHI99Y03	Chi Chi	TCU075, Nantou Tsaotun School	Class D (UBC97)	90	7.6	7.6	_	_	3.4	0.87	0.287	88.45	0.314	0.266	151.81	27.37
CHI99Y05	Chi Chi	TCU122, Changhua Ershui School	Class D (UBC97)	90	7.6	7.6	_	_	9.2	1	0.212	40.41	0.195	0.192	101.25	31.42
CHI99Y07	Chi Chi	TCU136	USGS (B)	EW	7.6	7.6	_	_	9	1	0.171	55.82	0.332	0.129	83.08	19.81

Table A.1. Continued

Country	**Date**	**Location**	**Site Geology**	**Comp**	**M_s**	**M_w**	**ED**	**HD**	**CD**	**Scale**	**PGA**	**PGV**	**V/A**	**EPA**	**EI**	**Δt_{eff}**
							(km)	**(km)**	**(km)**		**(g)**	**(cm/s)**	**(s)**	**(g)**		**(s)**
CHI99Y09	Chi Chi	CHY006	USGS (C)	EW	7.6	7.6	_	_	15	1	0.364	55.41	0.155	0.307	144.64	24.31
CHI99Y13	Chi Chi	WNT	USGS (C)	EW	7.6	7.6	_	_	1.2	1	0.958	68.75	0.073	0.631	112.67	27.08
CLI80X02	Campano-	Brienza	Stiff Soil	NS	6.9	6.5	43	_	_	1	0.227	11.27	0.051	0.212	30.02	10.23
CLI80Y04	Campano-	Calitri	Stiff Soil	EW	6.9	6.5	16	_	_	1	0.176	27.46	0.159	0.167	93.21	47.57
CMD92X02	Cape	Petrolia, General Store	Alluvium	0	7.1	7.0	_	_	16	1	0.589	48.30	0.084	0.363	96.02	17.90
CMD92Y02	Cape	Petrolia, General Store	Alluvium	90	7.1	7.0	_	_	16	1	0.662	89.45	0.138	0.437	150.92	16.11
COA83X01	Coalinga	Parkfield - Cholame 4W	Alluvium / Sandstone	0	6.5	6.5	_	58	_	1	0.131	10.51	0.082	0.133	25.65	13.26
DNZ76Y01	Denizli	Directorate of Public Works and Sett.	Stiff Soil	EW	5.1	_	15	_	_	1	0.261	15.46	0.060	0.258	23.22	5.91
DZC99X01	Düzce	Düzce	Soft Soil	NS	7.3	7.1	9.3	_	7	1	0.410	65.76	0.164	0.432	142.09	11.14
DZC99X02	Düzce	Bolu	Soil	NS	7.3	7.1	39	_	5.5	1	0.754	58.25	0.079	0.649	124.25	8.55
DZC99Y01	Düzce	Düzce	Soft Soil	EW	7.3	7.1	9.3	_	7	1	0.513	86.05	0.171	0.395	173.06	10.91
DZC99Y02	Düzce	Bolu	Soil	EW	7.3	7.1	39	_	5.5	1	0.822	66.92	0.083	0.492	123.54	9.03
ERZ92X01	Erzincan	Erzincan	Soil	NS	7.3	7.1	_	_	2	0.86	0.334	87.47	0.267	0.245	157.46	7.50
ERZ92Y01	Erzincan	Erzincan	Soil	EW	7.3	7.1	_	_	2	1	0.469	92.05	0.200	0.390	159.47	10.39
HOR83Y01	Horasan	Horasan Meteorology Station	Stiff Soil	EW	6.7	_	33	_	_	1	0.161	26.02	0.165	0.126	95.54	18.36

Table A.1. Continued

Country	Date	Location	Site Geology	Comp	M_s	M_w	ED (km)	HD (km)	CD (km)	Scale	PGA (g)	PGV (cm/s)	V/A (s)	EPA (g)	EI	Δt_{eff} (s)
IPV79X02	Imperial	El Centro Array #5, James Road	Alluvium	S50W	6.9	6.5	_	_	5.2	1	0.367	95.89	0.266	0.394	191.86	9.61
IPV79X03	Imperial	El Centro Array #6, Huston Road	Alluvium	S50W	6.9	6.5	_	_	3.5	0.87	0.381	98.52	0.264	0.268	183.15	8.24
IPV79X08	Imperial	Meloland Overpass	Alluvium	0	6.9	6.5	_	_	3.1	1	0.314	71.77	0.233	0.213	112.32	8.22
IPV79Y01	Imperial	El Centro Array #1, Borchard Ranch	Alluvium	S40E	6.9	6.5	_	_	23	1	0.141	16.43	0.119	0.112	32.19	16.17
IPV79Y02	Imperial	El Centro Array #5, James Road	Alluvium	S40E	6.9	6.5	_	_	5.2	1	0.550	49.71	0.092	0.415	122.22	8.21
IPV79Y08	Imperial	Meloland Overpass	Alluvium	270	6.9	6.5	_	_	3.1	1	0.296	90.45	0.311	0.223	186.69	6.75
IZM92X01	İzmir	Kusadasi Meteorology Station	Stiff Soil	L	6.0	_	41	_	_	1	0.067	4.34	0.066	0.059	9.03	10.59
KLM86X01	Kalamata	Kalamata-Prefecture	Stiff Soil	N265	5.8	_	9	_	_	1	0.215	32.73	0.155	0.216	59.88	5.50
KLM86X02	Kalamata	Kalamata-OTE Building	Stiff Soil	N80E	5.8	_	10	_	_	1	0.240	31.51	0.134	0.247	53.07	5.13
KLM86Y02	Kalamata	Kalamata-OTE Building	Stiff Soil	N10W	5.8	_	10	_	_	1	0.272	23.55	0.088	0.302	45.64	6.23
KOB95X01	Kobe	JMA	USGS (B)	NS	_	6.9	_	_	1	1	0.833	90.70	0.111	0.719	178.57	8.33
KOB95X02	Kobe	Nishi-Akashi	USGS (D)	0	_	6.9	_	_	11	1	0.509	37.27	0.075	0.563	89.97	9.72
KOB95X03	Kobe	Takarazu	USGS (D)	0	_	6.9	_	_	1.2	1	0.693	68.28	0.100	0.509	153.72	4.62
KOB95Y01	Kobe	JMA	USGS (B)	EW	_	6.9	_	_	1	1	0.629	75.04	0.122	0.532	146.83	9.54
KOB95Y02	Kobe	Nishi-Akashi	USGS (D)	90	_	6.9	_	_	11	1	0.503	36.60	0.074	0.429	81.60	11.23

Table A.1. Continued

Country	Date	Location	Site Geology	Comp	M_s	M_w	ED (km)	HD (km)	CD (km)	Scale	PGA (g)	PGV (cm/s)	V/A (s)	EPA (g)	EI	Δt_{eff} (s)
KOB95Y03	Kobe	Takarazu	USGS (D)	90	_	6.9	_	_	1.2	1	0.694	85.25	0.125	0.691	140.63	3.69
LAZ84Y02	Lazio	Cassino-Sant'Elia	Alluvium	EW	5.8	5.7	23	_	_	1	0.114	7.90	0.071	0.118	17.83	9.97
LND92X02	Landers	Amboy	Stiff Soil	0	7.5	7.3	_	_	73	1	0.115	17.86	0.158	0.119	69.01	34.80
LND92X04	Landers	Yermo Fire Station	Alluvium	360	7.5	7.3	_	_	31	1	0.151	29.03	0.195	0.174	66.75	21.37
LND92Y02	Landers	Amboy	Stiff Soil	90	7.5	7.3	_	_	73	1	0.146	20.07	0.140	0.142	73.86	31.47
LND92Y03	Landers	Joshua Tree Fire Station	Quaternary	90	7.5	7.3	_	_	10	1	0.284	42.71	0.153	0.211	127.32	28.22
LND92Y04	Landers	Yermo Fire Station	Alluvium	270	7.5	7.3	_	_	31	1	0.245	50.81	0.212	0.177	96.79	19.40
LPT89X01	Loma Prieta	Corralitos	Landslide Deposit	0	7.1	7.0	_	_	2.8	1	0.630	55.20	0.089	0.598	84.82	6.86
LPT89X02	Loma Prieta	Saratoga	Alluvium	0	7.1	7.0	_	_	4.1	1	0.504	41.35	0.084	0.295	94.42	9.40
LPT89X03	Loma Prieta	Hayward Muir School	Alluvium	0	7.1	7.0	_	_	45	1	0.170	13.63	0.082	0.177	38.00	12.81
LPT89X05	Loma Prieta	Capitola Fire Station	Alluvium	0	7.1	7.0	_	_	16	1	0.472	36.15	0.078	0.571	101.92	12.22
LPT89X06	Loma Prieta	Gilroy Array #2	USGS (C)	67	7.1	7.0	_	_	12	1	0.367	32.92	0.091	0.351	59.20	10.98
LPT89X12	Loma Prieta	Hollister, South St. &	Alluvium	0	7.1	7.0	_	_	17.2	1	0.369	62.78	0.173	0.266	146.10	16.45
LVM80X02	Livermore	Fagundes Ranch	Alluvium	270	5.8	_	_	11	_	1	0.250	9.74	0.040	0.212	9.81	3.22
MAR99X01	Marmara	Yarımca	Soft Soil	NS	7.8	7.4	15	_	3	1	0.322	79.60	0.252	0.214	158.44	15.76

Table A.1. Continued

Country	Date	Location	Site Geology	Comp	M_s	M_w	ED	HD	CD	Scale	PGA	PGV	V/A	EPA	EI	Δt_{eff}
							(km)	(km)	(km)		(g)	(cm/s)	(s)	(g)		(s)
MAR99X03	Marmara	Gebze	Stiff Soil	NS	7.8	7.4	42	_	15	1	0.269	45.59	0.173	0.186	80.09	7.53
MAR99X04	Marmara	Düzce	Soft Soil	NS	7.8	7.4	107	_	11	1	0.337	60.59	0.183	0.277	126.06	11.99
MAR99X09	Marmara	Kucuk Cekmece	Stiff Soil	NS	7.8	7.4	110	_	59	1	0.173	8.34	0.049	0.146	24.99	30.86
MAR99Y01	Marmara	Yarımca	Soft Soil	EW	7.8	7.4	15	_	3	1	0.230	84.70	0.375	0.217	165.41	15.31
MAR99Y02	Marmara	İzmit	Rock	EW	7.8	7.4	11	_	8	1	0.227	54.28	0.244	0.227	84.25	14.03
MAR99Y03	Marmara	Gebze	Stiff Soil	EW	7.8	7.4	42	_	15	1	0.143	34.72	0.247	0.149	51.16	8.47
MAR99Y05	Marmara	Sakarya	Stiff Soil / Rock	EW	7.8	7.4	40	_	7	1	0.407	79.80	0.200	0.293	94.78	15.52
MGH84X01	Morgan Hill	Gilroy Array #2 (Hwy 101 & Bolsa Rd)	Alluvium	0	6.1	6.1	_	_	12	1	0.157	4.99	0.032	0.099	17.56	18.94
MGH84Y03	Morgan Hill	Gilroy Array #7 (Mantelli Ranch)	Alluvium / Sandstone	90	6.1	6.1	_	_	7.9	1	0.114	5.76	0.052	0.132	11.54	12.10
MGH84Y04	Morgan Hill	Coyote Lake Dam	Rock	285	6.1	6.1	_	_	1.5	1	1.298	80.79	0.063	0.672	96.44	3.19
MNJ90X02	Manjil	Buil. & Hou. Research Center, Tehran	Stiff Soil	NS	7.3	_	234	_	_	1	0.011	1.09	0.098	0.012	3.56	14.63
MNJ90Y01	Manjil	Abhar	Soft Soil	T	7.3	_	98	_	_	1	0.209	55.44	0.271	0.252	190.86	21.11
MNJ90Y02	Manjil	Buil. & Hou. Research Center, Tehran	Stiff Soil	EW	7.3	_	234	_	_	1	0.013	1.24	0.098	0.013	2.92	13.61
MTN79X01	Montenegro	Petrovac, Hotel Oliva	Stiff Soil	NS	7.0	_	25	_	_	1	0.454	38.82	0.087	0.461	87.07	12.00
MTN79Y01	Montenegro	Petrovac, Hotel Oliva	Stiff Soil	EW	7.0	_	25	_	_	1	0.306	25.31	0.084	0.310	47.24	13.36

Table A.1. Continued

Country	Date	Location	Site Geology	Comp	M_s	M_w	ED	HD	CD	Scale	PGA	PGV	V/A	EPA	EI	Δt_{eff}
							(km)	(km)	(km)		(g)	(cm/s)	(s)	(g)		(s)
MTN79Y02	Montenegro	Ulcinj, Hotel Olimpic	Stiff Soil	EW	7.0	_	24	_	_	1	0.241	47.08	0.199	0.193	99.62	25.99
NRD94X05	Northridge	Katherine Rd, Simi Valley	Alluvium	N00E	6.8	6.7	_	_	14	1	0.727	51.11	0.072	0.519	87.62	5.93
NRD94X06	Northridge	Rinaldi Receiving Station	Alluvium	N41W	6.8	6.7	_	_	8.6	1	0.480	80.33	0.171	0.500	164.22	8.38
NRD94X07	Northridge	Slymar, Converter Station	Alluvium	N38W	6.8	6.7	_	_	8.7	0.9	0.521	96.52	0.189	0.288	203.32	5.22
NRD94X08	Northridge	Leona Valley, Ritter Ranch	Alluvium	0	6.8	6.7	_	_	41	1	0.146	14.88	0.104	0.111	29.49	14.47
NRD94X09	Northridge	Downey County Maint. Bldg.	Alluvium	360	6.8	6.7	_	_	46	1	0.223	12.70	0.058	0.201	33.38	17.53
NRD94X10	Northridge	Santa Monica, City Hall Grounds	Alluvium	360	6.8	6.7	_	_	27	1	0.370	24.91	0.069	0.273	75.96	11.31
NRD94X12	Northridge	Castaic Old Ridge Road	Sandstone	360	6.8	6.7	_	_	24	1	0.514	52.56	0.104	0.420	118.59	8.69
NRD94X13	Northridge	Newhall LA County Fire Station	Alluvium	360	6.8	6.7	_	_	11	1	0.589	94.72	0.164	0.582	175.86	5.53
NRD94X15	Northridge	Tarzana Cedar Hill Nursery	Alluvium	360	6.8	6.7	_	_	17	1	0.990	77.18	0.080	0.946	164.09	12.63
NRD94X19	Northridge	Sepulveda VA Hospital	Alluvium	270	6.8	6.7	_	_	9.5	1	0.753	84.85	0.115	0.489	127.40	7.84
NRD94Y05	Northridge	Katherine Rd, Simi Valley	Alluvium	N90E	6.8	6.7	_	_	14	1	0.513	44.56	0.088	0.588	77.27	6.76
NRD94Y13	Northridge	Newhall LA County Fire Station	Alluvium	90	6.8	6.7	_	_	11	1	0.583	74.84	0.131	0.631	129.90	5.93
NRD94Y14	Northridge	Pacoima Kagel Canyon	Tertiary Sandstone	90	6.8	6.7	_	_	11	1	0.301	30.95	0.105	0.265	88.56	10.38
NRD94Y15	Northridge	Tarzana Cedar Hill Nursery	Alluvium	90	6.8	6.7	_	_	17	0.89	1.574	97.49	0.063	1.209	148.89	10.57

Table A.1. Continued

Country	Date	Location	Site Geology	Comp	M_s	M_w	ED	HD	CD	Scale	PGA	PGV	V/A	EPA	EI	Δt_{eff}
							(km)	(km)	(km)		(g)	(cm/s)	(s)	(g)		(s)
NRD94Y19	Northridge	Sepulveda VA Hospital	Alluvium	360	6.8	6.7	_	_	9.5	1	0.939	76.60	0.083	0.807	146.38	8.19
NRD94Y21	Northridge	Saticoy	Alluvium	180	6.8	6.7	_	_	13	1	0.477	61.48	0.131	0.507	155.83	10.61
NRD94Y22	Northridge	Jensen Filter Plant	Alluvium	292	6.8	6.7	_	_	8.6	1	0.593	99.28	0.171	0.448	228.28	5.97
SFE71X01	San	8244 Orion Blvd.	Alluvium	N00W	6.5	6.6	_	_	17	1	0.255	29.80	0.119	0.233	98.78	16.58
TBS78X02	Tabas	Tabas	Stiff Soil	N74E	7.3	_	52	_	_	1	0.914	90.23	0.101	0.828	217.21	18.46
TBS78Y02	Tabas	Tabas	Stiff Soil	N16W	7.3	_	52	_	_	1	1.065	80.53	0.077	0.909	212.25	18.04
VRN90X02	Vrancea	Bucharest, Building Research Institute	Alluvium	NS	6.8	_	162	_	_	1	0.038	6.45	0.173	0.027	9.61	8.53
VRN90Y02	Vrancea	Bucharest, Building Research Institute	Alluvium	EW	6.8	_	162	_	_	1	0.054	2.08	0.040	0.036	3.62	8.53
WHN87X01	Whittier	Fremont School, Alhambra	Alluvium	180	5.8	6.1	_	_	14	1	0.292	21.72	0.076	0.296	32.01	5.25
WHN87X02	Whittier	Cedar Hill Nursery, Tarzana	Alluvium / Siltstone	0	5.8	6.1	_	_	41	1	0.405	19.16	0.048	0.414	27.71	6.63
WHN87Y01	Whittier	Fremont School, Alhambra	Alluvium	270	5.8	6.1	_	_	14	1	0.381	16.95	0.045	0.267	26.98	5.71

APPENDIX B

B.1. OpenSees Code Files for 2D Portal Frame

```
# ------------------------------------------------------------------
# 2D Wide Beam Portal Frame
# NonlinearBeamColumn element, inelastic fiber section
# ENES KARAASLAN
# SET UP -----------------------------------------------------------
wipe;                    # clear memory of all past model definitions
model BasicBuilder -ndm 2 -ndf 3;        # Define the model builder,
ndm=#dimension, ndf=#dofs

# define GEOMETRY --------------------------------------------------
set LCol [expr 2.9*$m];            # column length
set LBeam [expr 6.*$m];            # beam length
set Weight [expr 250.*$KN];        # superstructure weight
# define section geometry
set HCol [expr 240.*$mm];          # Column Depth
set BCol [expr 240.*$mm];          # Column Width
set BArea [expr 86400.*$mm2];      # Beam area is fixed
set BBeam [expr $BBeam*$mm];       # unit has been inserted
set HBeam [expr $BArea/($BBeam*$mm)];     # Beam Depth

# calculated parameters
set PCol [expr $Weight/2];         # nodal dead-load weight per column
set Mass [expr $PCol/$g];          # nodal mass
set MCol [expr 1./12.*($Weight/$LBeam)*pow($LBeam,2)];# beam-end
moment due to distributed load.
# calculated geometry parameters
set ACol [expr $BCol*$HCol];                         # cross-sectional
area
set ABeam [expr $BBeam*$HBeam];
set IzCol [expr 1./12.*$BCol*pow($HCol,3)];          # Column moment
of inertia
set IzBeam [expr 1./12.*$BBeam*pow($HBeam,3)];       # Beam moment of
inertia

# nodal coordinates:
node 1 0 0;              # node#, X, Y
node 2 $LBeam 0
node 3 0 $LCol
node 4 $LBeam $LCol

# Single point constraints -- Boundary Conditions
fix 1 1 1 0;                   # node DX DY RZ
fix 2 1 1 0;                   # node DX DY RZ
fix 3 0 0 0
fix 4 0 0 0

# nodal masses:
mass 3 $Mass  0. 0.;           # node#, Mx My Mz, Mass=Weight/g, neglect
rotational inertia at nodes
mass 4 $Mass  0.  0.
```

```
# Define ELEMENTS & SECTIONS ------------------------------------------
set ColSecTag 1;              # assign a tag number to the column
section
set BeamSecTag 2;             # assign a tag number to the beam section
# define section geometry
set coverCol [expr 40.*$mm];        # Column cover to reinforcing steel
NA.
set coverBeam [expr 40.*$mm];       # Beam cover to reinforcing steel
NA.
set AsCol [expr 314.*$mm2];   # area of longitudinal-reinforcement bars
set AsBeam [expr 201*$mm2]

# MATERIAL parameters -------------------------------------------------
set IDconcU 1;                # material ID tag -- unconfined cover
concrete
set IDconcC 2;                # material ID tag -- confined core
concrete
set IDreinf 3;                # material ID tag -- reinforcement
# nominal concrete compressive strength
set fc [expr -25*$MPa];       # CONCRETE Compressive Strength, ksi
(+Tension, -Compression)
set Ec [expr 3407.5*$ksi]
# set Ec [expr 4700*$MPa*sqrt(-$fc)];     # Concrete Elastic Modulus
# unconfined concrete
set fc1U $fc;                       # UNCONFINED concrete (todeschini
parabolic model), maximum stress
set eps1U -0.003;             # strain at maximum strength of
unconfined concrete
set fc2U [expr 0.2*$fc1U];    # ultimate stress
set eps2U   -0.05;                  # strain at ultimate stress
set lambda 0.1;                     # ratio between unloading slope at
$eps2 and initial slope $Ec
# Confined concrete
set fc1C [expr 1.26394*$fc]; # CONFINED concrete (mander model),
maximum stress
set eps1C   [expr 2.*$fc1C/$Ec];    # strain at maximum stress
set fc2C $fc;     # ultimate stress
set eps2C [expr 5*$eps1C];    # strain at ultimate stress
# tensile-strength properties
set ftU [expr -0.14*$fc1U];   # tensile strength +tension
set ftC [expr -$fc1C/10.];    # tensile strength +tension
set Ets [expr $ftU/0.002];    # tension softening stiffness
# -----------
set Fy [expr 420.*$MPa];      # STEEL yield stress
set Es [expr 200000.*$MPa];   # modulus of steel
set epsY [expr $Fy/$Es];      # steel yield strain
set Bs 0.01;                  # strain-hardening ratio
set R0 18;                    # control the transition from elastic to
plastic branches
set cR1 0.925;# control the transition from elastic to plastic
branches
set cR2 0.15;# control the transition from elastic to plastic branches
uniaxialMaterial Concrete02 $IDconcU $fc1U $eps1U $fc2U $eps2U $lambda
$ftU $Ets;  # Cover Concrete (unconfined)
uniaxialMaterial Concrete02 $IDconcC $fc1C $eps1C $fc2C    $eps2C
$lambda $ftC $Ets;      # Core Concrete (confined)
```

```
uniaxialMaterial Steel02 $IDreinf $Fy $Es $Bs $R0 $cR1 $cR2;
      # build reinforcement material
# FIBER SECTION properties ------------------------------------------
------------------
# symmetric section
#                        y
#                        ^
#                        |
#             ---------------------     --   --
#             |   o     o     o    |     |    -- cover
#             |                    |     |
#             |                    |     |
#    z <---   |         +          |     H
#             |                    |     |
#             |                    |     |
#             |   o     o     o    |     |    -- cover
#             ---------------------     --   --
#             |-------- B --------|
#
# RC column section:
   set y1 [expr $HCol/2.0];   # The distance from the section z-axis to
the edge of the cover concrete -- outer edge of cover concrete
   set z1 [expr $BCol/2.0];   # The distance from the section y-axis to
the edge of the cover concrete -- outer edge of cover concrete
   set coreY [expr $y1-$coverCol]
   set coreZ [expr $z1-$coverCol]
section fiberSec $ColSecTag   {;    # Define the fiber section
      # Create the concrete core fibers
patch quadr $IDconcC 10 10 -$coreZ -$coreY $coreZ -$coreY $coreZ
$coreZ -$coreZ $coreY
      # Create the concrete cover fibers (top, bottom, left, right)
patch quadr $IDconcU 10 2 -$z1 $coreY $z1 $coreY $z1 $y1 -$z1 $y1
patch quadr $IDconcU 10 2 -$z1 -$y1 $z1 -$y1 $z1 -$coreY -$z1 -$coreY
patch quadr $IDconcU 10 10 -$z1 -$coreY -$coreZ -$coreY -$coreZ $coreY
-$z1 $coreY
patch quadr $IDconcU 10 10 $coreZ -$coreY $z1 -$coreY $z1 $coreY
$coreZ $coreY
      # Create the reinforcing fibers (left, middle, right)
layer straight $IDreinf 3 $AsCol -$coreZ $coreY $coreZ $coreY;   # top
layer reinforcement
layer straight $IDreinf 3 $AsCol -$coreZ -$coreY $coreZ -$coreY; #
bottom layer reinforcement
 };   # end of fibersection definition
# BEAM section:
set y2 [expr $HBeam/2.0]
set z2 [expr $BBeam/2.0]
set coreY [expr $y2-$coverBeam]
set coreZ [expr $z2-$coverBeam]
section Fiber 2 {
# Create the concrete core fibers
patch quadr $IDconcC 10 10 -$coreZ -$coreY $coreZ -$coreY $coreZ
$coreZ -$coreZ $coreY
# Create the concrete cover fibers (top, bottom, left, right)
patch quadr $IDconcU 10 2 -$z2 $coreY $z2 $coreY $z2 $y2 -$z2 $y2
patch quadr $IDconcU 10 2 -$z2 -$y2 $z2 -$y2 $z2 -$coreY -$z2 -$coreY
patch quadr $IDconcU 10 10 -$z2 -$coreY -$coreZ -$coreY -$coreZ $coreY
-$z2 $coreY
```

```
patch quadr $IDconcU 10 10 $coreZ -$coreY $z2 -$coreY $z2 $coreY
$coreZ $coreY
# Create the reinforcing fibers (left, middle, right)
layer straight $IDreinf 5 $AsBeam -$coreZ -$coreY $coreZ -$coreY;
      # bottom layer reinforcement
}
# define geometric transformation: performs a linear geometric
transformation of beam stiffness and resisting force from the basic
system to the global-coordinate system
set ColTransfTag 1;     # associate a tag to column transformation
set BeamTransfTag 2;    # associate a tag to beam transformation (good
practice to keep col and beam separate)
set ColTransfType Linear ;    # options, Linear PDelta Corotational
geomTransf $ColTransfType $ColTransfTag ;       # only columns can have
PDelta effects (gravity effects)
geomTransf Linear $BeamTransfTag  ;

# element connectivity:
set numIntgrPts 5;                                                  #
number of integration points for force-based element
element nonlinearBeamColumn 1 1 3 $numIntgrPts $ColSecTag
$ColTransfTag;    # self-explanatory when using variables
element nonlinearBeamColumn 2 2 4 $numIntgrPts $ColSecTag
$ColTransfTag;
element nonlinearBeamColumn 3 3 4 $numIntgrPts $BeamSecTag
$BeamTransfTag;

# Define RECORDERS -------------------------------------------------------
recorder Node -file $dataDir/$Outdir -time -node 3 4 -dof 1 disp;


# define GRAVITY ---------------------------------------------------------
set WzBeam [expr $Weight/$LBeam];
pattern Plain 1 Linear {
   eleLoad -ele 3 -type -beamUniform -$WzBeam ; # distributed
superstructure-weight on beam
}
# Gravity-analysis parameters -- load-controlled static analysis
set Tol 1.0e-8;               # convergence tolerance for test
constraints Plain;                  # how it handles boundary
conditions
numberer Plain;               # renumber dof's to minimize band-width
(optimization), if you want to
system BandGeneral;           # how to store and solve the system of
equations in the analysis
test NormDispIncr $Tol 6 ;          # determine if convergence has been
achieved at the end of an iteration step
algorithm Newton;             # use Newton's solution algorithm:
updates tangent stiffness at every iteration
set NstepGravity 10;          # apply gravity in 10 steps
set DGravity [expr 1./$NstepGravity];     # first load increment;
integrator LoadControl $DGravity;   # determine the next time step for
an analysis
analysis Static;              # define type of analysis static or
transient
analyze $NstepGravity;        # apply gravity
# ------------- maintain constant gravity loads and reset time to zero
loadConst -time 0.0
```

```
puts "Model Built"

# ---------------------------------------------------------------------------
# 2D Wide Beam Portal Frame
# NonlinearBeamColumn element, inelastic fiber section
# ENES KARAASLAN
# TIME HISTORY ANALYSIS---------------------------------------------------

# Uniform Earthquake ground motion (uniform acceleration input at all
support nodes)
set GMdirection 1;                    # ground-motion direction
set GMfile "H-e12140" ;               # ground-motion file names
set GMfact 1.5;                       # ground-motion scaling factor
# set up ground-motion-analysis parameters
set DtAnalysis    [expr 0.01*$sec]; # time-step Dt for lateral analysis
set TmaxAnalysis  [expr 25. *$sec]; # maximum duration of ground-motion
analysis should be 50*$sec

# ----------- set up analysis parameters
source LibAnalysisDynamicParameters.tcl;  #

# define DAMPING-----------------------------------------------------------
# apply Rayleigh DAMPING from $xDamp
set xDamp 0.05;                 # 5% damping ratio
set lambda [eigen 1];           # eigenvalue mode 1
set omega [expr pow($lambda,0.5)];
set alphaM 0.;                  # M-prop. damping; D = alphaM*M
set betaKcurr 0.;               # K-proportional damping;
set betaKcomm [expr 2.*$xDamp/($omega)];
set betaKinit 0.;               # initial-stiffness proportional damping
rayleigh $alphaM $betaKcurr $betaKinit $betaKcomm; # RAYLEIGH damping

#  --------------------- perform Dynamic Ground-Motion Analysis
set IDloadTag 400;      # for uniformSupport excitation

# read a PEER strong motion database file, extracts dt from the header
and converts the file to the format OpenSees expects for
Uniform/multiple-support ground motions
source ReadSMDFile.tcl; # read in procedure Multinition

# Uniform EXCITATION: acceleration input
set inFile $GMdir/$GMfile.at2
set outFile $GMdir/$GMfile.g3;      # set variable holding new filename
ReadSMDFile $inFile $outFile dt;    # call procedure to convert the
ground-motion file
set GMfatt [expr $g*$GMfact];       # data in input file is in g Unifts

-- ACCELERATION with time series information
set AccelSeries "Series -dt $dt -filePath $outFile -factor  $GMfatt";
pattern UniformExcitation  $IDloadTag  $GMdirection -accel
$AccelSeries;           # create Uniform excitation
set Nsteps [expr int($TmaxAnalysis/$DtAnalysis)];
set ok [analyze $Nsteps $DtAnalysis];
if {$ok != 0} {  ;      # analysis was not successful.
      # ---------------------------------------------------------------
      # change some analysis parameters to achieve convergence
      # performance is slower inside this loop
      # Time-controlled analysis
```

```
	set ok 0;
	set controlTime [getTime];
	while {$controlTime < $TmaxAnalysis && $ok == 0} {
		set controlTime [getTime]
		set ok [analyze 1 $DtAnalysis]
		if {$ok != 0} {
			puts "Trying Newton with Initial Tangent .."
			test NormDispIncr   $Tol 1000  0
			algorithm Newton -initial
			set ok [analyze 1 $DtAnalysis]
			test $testTypeDynamic $TolDynamic $maxNumIterDynamic
0
			algorithm $algorithmTypeDynamic
		}
		if {$ok != 0} {
			puts "Trying Broyden .."
			algorithm Broyden 8
			set ok [analyze 1 $DtAnalysis]
			algorithm $algorithmTypeDynamic
		}
		if {$ok != 0} {
			puts "Trying NewtonWithLineSearch .."
			algorithm NewtonLineSearch .8
			set ok [analyze 1 $DtAnalysis]
			algorithm $algorithmTypeDynamic
		}
	}
};	# end if ok !0

puts "Ground Motion Done. End Time: [getTime]"
```

B.2. OpenSees Code Files for Hysteresis Calibration

```
# ---------------------------------------------------------------------
# Wide Beam Column Joint Behavior SPECIMEN IL
# With Ibarra-Krawinkler Deterioration Model
# ENES KARAASLAN

########################################################################
#          Set Up & Source Definition                                  #
########################################################################
wipe all;                    # clear memory of past model definitions
model BasicBuilder -ndm 2 -ndf 3;
source units.tcl
source IbarraMatIL.tcl
source rotSpring2D.tcl
source DisplayModel2D.tcl
source DisplayPlane.tcl

########################################################################
#          Define Analysis Type                                        #
########################################################################
# Define type of analysis:  "pushover" = pushover;  "dynamic" =
dynamic
      set analysisType "cyclic";

      if {$analysisType == "pushover"} {
            set dataDir Concentrated-Pushover-Output;
            file mkdir $dataDir;          # create output folder
      }
      if {$analysisType == "cyclic"} {
            set dataDir Concentrated-Cyclic-Output;
            file mkdir $dataDir;          # create output folder
      }
      if {$analysisType == "dynamic"} {
            set dataDir Concentrated-Dynamic-Output;
            file mkdir $dataDir;          # create output folder
      }

########################################################################
#          Define Building Geometry, Nodes, and Constraints            #
########################################################################

# define nodal masses and forces
      set PCol [expr 200.*$KN];     # Axial load applied to the column
      set PBeam [expr 40.*$KN];     # Point load applied the the beams
      set NodalMass [expr ($PCol+2*$PBeam)/$g]; # Nodal mass
      set Negligible 1e-9;          # a very small number
      set LCol [expr 725.*$mm];     # column length
      set LBeam [expr 1475.*$mm];   # beam length
```

```
# define nodes and assign masses to the beam-column joint
      node 1 0. 0.;
      node 2 0. [expr 1.0*$LCol] -mass $NodalMass $Negligible
$Negligible;
      node 3 0. [expr 2.0*$LCol]
      node 4 $LBeam [expr 1.0*$LCol]
      node 5 -$LBeam [expr 1.0*$LCol]
# define extra nodes for plastic hinge rotational springs
      #node 12 0. 0.
      node 21 0. [expr 1.0*$LCol]
      node 23 0. [expr 1.0*$LCol]
      node 24 0. [expr 1.0*$LCol]
      node 25 0. [expr 1.0*$LCol]
# assign boundary condidtions
      fix 1 1 1 0;
      fix 4 0 1 0
      fix 5 0 1 0

#######################################################################
#          Define Section Properties and Elements                     #
#######################################################################

# Define GEOMETRY and LOADING parameters -----------------------------
set LCol [expr 725.*$mm];           # column length
set LBeam [expr 1475.*$mm];         # beam length
set HCol [expr 270.*$mm];           # Column depth
set BCol [expr 270.*$mm];           # Column width
set BBeam [expr 480.*$mm];          # Beam width
set HBeam [expr 180.*$mm];          # Beam depth
set ABeam [expr $BBeam*$HBeam];     # Beam area
set Dy [expr 59.*$mm];
set ACol [expr $HCol*$BCol];        # Column cross-sectional area
set ABeam [expr $BBeam*$HBeam];     # Beam cross-sectional area
set IzCol [expr 1./12.*$BCol*pow($HCol,3)]; # Column momentofinertia
set IzBeam [expr 1./12.*$BBeam*pow($HBeam,3)]; # Beam momentofinertia
set fc [expr 24.9*$MPa];            # 28 day concrete strength
set EConc [expr 23700*$MPa];        # ACI Code concrete elastic modulus

# set up geometric transformations of element
set PDeltaTransf 1;
geomTransf PDelta $PDeltaTransf;    # PDelta transformation

# define rotational spring material,
# IL wide-beam spring material
IbarraMat 1 1935.3 52.8 -57.4 0.050 0.100 1.22;
# IL column-lower spring material
IbarraMat 2 4019.0 81.4 -81.4 0.028 0.041 1.20;
# IL column-upper spring material
IbarraMat 3 4019.0 67.2 -67.2 0.020 0.025 1.20;

# define elastic beam and column elements using "element" command
element elasticBeamColumn  1 1 21 $ACol $EConc $IzCol $PdeltaTransf
element elasticBeamColumn  2 23 3 $ACol $EConc $IzCol $PDeltaTransf;
element elasticBeamColumn  3 24 4 $ABeam $EConc $IzBeam $PDeltaTransf;
element elasticBeamColumn  4 25 5 $ABeam $EConc $IzBeam $PDeltaTransf;
```

```
# define zero length elements for rotational springs
#rotSpring2D 12 1 12 2
rotSpring2D 21 2 21 2
rotSpring2D 23 2 23 3
rotSpring2D 24 2 24 1
rotSpring2D 25 2 25 1

# display the model with the node numbers
DisplayModel2D NodeNumbers

######################################################################
#               Gravity Loads & Gravity Analysis                     #
######################################################################
# apply gravity loads
#command: pattern PatternType $PatternID TimeSeriesType
pattern Plain 101 Constant {
      # point loads on column nodes
      set P_F2 $PCol;
      load 3 0.0 $P_F2 0.0;
}

# Gravity-analysis: load-controlled static analysis
set Tol 1.0e-6;         # convergence tolerance for test
constraints Plain;      # how it handles boundary conditions
numberer RCM;           # renumber dof's to minimize band-width
system BandGeneral;     # how to store and solve the systemofequations
test NormDispIncr $Tol 6;     # determine if convergence has been
achieved at the end of an iteration step
algorithm Newton;             # use Newton's solution algorithm:
updates tangent stiffness at every iteration
set NstepGravity 10;    # apply gravity in 10 steps
set DGravity [expr 1.0/$NstepGravity];    # load increment
integrator LoadControl $DGravity;  # determine the next time step
analysis Static;        # define type of analysis: static or transient
analyze $NstepGravity;  # apply gravity

# maintain constant gravity loads and reset time to zero
loadConst -time 0.0
puts "Model Built"

######################################################################
#                                  Recorders                         #
######################################################################

# record top diplacement
recorder Node -file $dataDir/JointDispCyc.out -time -node 3 -dof 1
disp;

# record applied force
recorder Element -file  $dataDir/AppliedForceCyc.out -ele 2
globalForce;
```

```
######################################################################
#                                                                    #
#                          Analysis Section                          #
#                                                                    #
######################################################################

######################################################################
#                          Pushover Analysis                         #
######################################################################

if {$analysisType == "pushover"} {
	puts "Running Pushover Analysis..."
	# assign lateral loads and create load pattern
	set lat2 1; # asmall force applied to prevent convergence errors.
	pattern Plain 200 Linear {
		load 3 $lat2 0.0 0.0;
	}
# displacement parameters
	set IDctrlNode 3; # node where disp is read for disp control
	set IDctrlDOF 1;  # degree of freedom read for disp control
	set Dmax [expr 10.0*$Dy];     # maximum displacement of pushover
	set Dincr [expr 0.0005*$Dy];  # displacement increment

# analysis commands
	constraints Plain;      # how it handles boundary conditions
	numberer RCM;           # renumber dof's to minimize band-width
	system BandGeneral;     # how to store and solve the system of
	equations in the analysis (large model: try UmfPack)
	test NormUnbalance 1.0e-6 400; # tolerance, max iterations
	algorithm Newton;                # use Newton's solution algorithm
	integrator DisplacementControl  $IDctrlNode   $IDctrlDOF $Dincr;
	analysis Static;  # define type of analysis: static for pushover
	set Nsteps [expr int($Dmax/$Dincr)];# number of analysis steps
	set ok [analyze $Nsteps];
	puts "Pushover complete
}



######################################################################
#                        Cyclic Analysis                             #
######################################################################

if {$analysisType == "cyclic"} {
	puts "Running Cyclic Analysis..."
# assign lateral loads and create load pattern
	set lat2 1;
	pattern Plain 200 Linear {
		load 3 -$lat2 0.0 0.0;
	}
# display deformed shape:
	set ViewScale 5;
	DisplayModel2D DeformedShape $ViewScale ;
```

```
# ---------------------------------------------------------------------

      # we need to set up parameters that are particular to the model.
      set IDctrlNode 3;
      set IDctrlDOF 1;
      # characteristics of pushover analysis
      set iDmax "0.5  0.75 1.0 1.5 2.0 3.0";# vector of displacement-
cycle peaks, in terms of expected yield displacement
      set Dincr [expr 0.01*$Dy];# displacement increment for pushover.
      set Fact $Dy;     # scale drift ratio by expected yield
displacement for displacement cycles
      set CycleType Full;     # you can do Full / Push / Half cycles
      set Ncycles 3;     # specify the number of cycles at each peak

# set up analysis parameters
      source LibAnalysisStaticParameters.tcl;

# perform Static Cyclic Displacements Analysis
      source GeneratePeaks.tcl
      set fmt1 "%s Cyclic analysis: CtrlNode %.1i, dof %.1i, Disp=%.3f
%s";  # format for screen/file output of DONE/PROBLEM analysis
      foreach Dmax $iDmax {
            set iDstep [GeneratePeaks $Dmax $Dincr $CycleType $Fact];
      # this proc is defined above
            for {set i 1} {$i <= $Ncycles} {incr i 1} {
                  set zeroD 0
                  set D0 0.0
                  foreach Dstep $iDstep {
                        set D1 $Dstep
                        set Dincr [expr $D1 - $D0]
                        integrator DisplacementControl  $IDctrlNode
$IDctrlDOF $Dincr
                        analysis Static
                        # ------------first analyze command------------
                        set ok [analyze 1]
                        # -----------if convergence failure------------
                        if {$ok != 0} {
                        # if analysis fails, we try some other stuff
                        # performance is slower inside this loop

                              if {$ok != 0} {
                                    puts "Trying Newton with Initial
Tangent .."

                                    test NormDispIncr   $Tol 2000 0
                                    algorithm Newton -initial
                                    set ok [analyze 1]
                                    test $testTypeStatic $TolStatic
$maxNumIterStatic     0

                                    algorithm $algorithmTypeStatic
                              }
                              if {$ok != 0} {
                                    puts "Trying Broyden .."
                                    algorithm Broyden 8
                                    set ok [analyze 1 ]
                                    algorithm $algorithmTypeStatic
                              }
                              if {$ok != 0} {
                                    puts "Trying NewtonWithLineSearch"
```

```
                                                algorithm NewtonLineSearch 0.8
                                                set ok [analyze 1]
                                                algorithm $algorithmTypeStatic
                                          }
                                          if {$ok != 0} {
                                                set putout [format $fmt1 "PROBLEM"
$IDctrlNode $IDctrlDOF [nodeDisp $IDctrlNode $IDctrlDOF] $LunitTXT]
                                                puts $putout
                                                return -1
                                          }; # end if
                                    }; # end if
                                    # ----------------------------------------
                                    set D0 $D1;             # move to next step
                              }; # end Dstep
                        };    # end i
      };    # end of iDmaxCycl
      # ---------------------------------------------------------------
      if {$ok != 0 } {
            puts [format $fmt1 "PROBLEM" $IDctrlNode $IDctrlDOF
[nodeDisp $IDctrlNode $IDctrlDOF] $LunitTXT]
      } else {
            puts "CYCLIC ANALYSIS COMPLETED."
      }
}

######################################################################
#   Time History/Dynamic Analysis                                    #
######################################################################

if {$analysisType == "dynamic"} {
      puts "Running dynamic analysis..."
      # display deformed shape:
      set ViewScale 5;  # amplify display of deformed shape
      DisplayModel2D DeformedShape $ViewScale;
      # Rayleigh Damping
      # calculate damping parameters
      set zeta 0.02;    # percentage of critical damping
      set a0 [expr $zeta*2.0*$w1*$w2/($w1 + $w2)];
      set a1 [expr $zeta*2.0/($w1 + $w2)];
      set a1_mod [expr $a1*(1.0+$n)/$n];
      # assign damping to frame beams and columns
      region 4 -eleRange 111 222 -rayleigh 0.0 0.0 $a1_mod 0.0;
      region 5 -node 12 13 22 23 -rayleigh $a0 0.0 0.0 0.0;
      # define ground motion parameters
      set patternID 1;              # load pattern ID
      set GMdirection 1;            # ground motion direction (1 = x)
      set GMfile "NR94cnp.tcl";     # ground motion filename
      set dt 0.01;                  # timestep of input GM file
      set Scalefact 1.0;            # ground motion scaling factor
      set TotalNumberOfSteps 2495;  # number of steps in ground motion
      set GMtime [expr $dt*$TotalNumberOfSteps + 10.0];
      # define the acceleration series for the ground motion
      set accelSeries "Series -dt $dt -filePath $GMfile -factor [expr
      $Scalefact*$g]";
```

```
# create load pattern:
pattern UniformExcitation $patternID $GMdirection -accel $accelSeries;

# define dynamic analysis parameters
set dt_analysis 0.001;
wipeAnalysis;
constraints Plain;
numberer RCM;
system UmfPack;
test NormDispIncr 1.0e-8 50;
algorithm NewtonLineSearch;
integrator Newmark 0.5 0.25;
analysis Transient;
set NumSteps [expr round(($GMtime + 0.0)/$dt_analysis)];

# perform the dynamic analysis
set ok [analyze $NumSteps $dt_analysis]; # ok = 0 if analysis was
completed
if {$ok == 0} {
      puts "Dynamic analysis complete";
} else {
      puts "Dynamic analysis did not converge";
}

# output time at end of analysis
set currentTime [getTime];
puts "The current time is: $currentTime";
wipe all;
}

wipe all;
```

```
# -------------------------------------------------------------------
# Wide Beam Column Joint Behavior SPECIMEN UL
# With Ibarra-Krawinkler Deterioration Model
# ENES KARAASLAN

#####################################################################
#          Set Up & Source Definition
#####################################################################
wipe all;               # clear memory of past model definitions
model BasicBuilder -ndm 2 -ndf 3;   # Define the model builder, ndm =
#dimension, ndf = #dofs
source units.tcl
source IbarraMatUL.tcl
source rotSpring2D.tcl
source DisplayModel2D.tcl
source DisplayPlane.tcl

#####################################################################
#                       Define Analysis Type                        #
#####################################################################

# Define type of analysis:  "pushover" = pushover;  "dynamic" =
dynamic

      set analysisType "pushover";

      if {$analysisType == "pushover"} {
            set dataDir Concentrated-Pushover-Output;
            file mkdir $dataDir;
      }
      if {$analysisType == "cyclic"} {
            set dataDir Concentrated-Cyclic-Output;
            file mkdir $dataDir;
      }
      if {$analysisType == "dynamic"} {
            set dataDir Concentrated-Dynamic-Output;
            file mkdir $dataDir;
      }

#####################################################################
#          Define Building Geometry, Nodes, and Constraints         #
#####################################################################

# define nodal masses and forces
      set PCol [expr 75.*$KN];      # Axial load applied to the column
      set PBeam [expr 40.*$KN];     # Point load applied the the beams
      set NodalMass [expr ($PCol+2*$PBeam)/$g]; # Nodal mass
      set Negligible 1e-9;          # a very small number
      set LCol [expr 725.*$mm];     # column length
      set LBeam [expr 1475.*$mm];   # beam length
```

```
# define nodes and assign masses to the beam-column joint
	node 1 0. 0.;
	node 2 0. [expr 1.0*$LCol] -mass $NodalMass $Negligible
$Negligible;
	node 3 0. [expr 2.0*$LCol]
	node 4 $LBeam [expr 1.0*$LCol]
	node 5 -$LBeam [expr 1.0*$LCol]
# define extra nodes for plastic hinge rotational springs
	#node 12 0. 0.
	node 21 0. [expr 1.0*$LCol]
	node 23 0. [expr 1.0*$LCol]
	node 24 0. [expr 1.0*$LCol]
	node 25 0. [expr 1.0*$LCol]

# assign boundary condidtions
	fix 1 1 1 0;
	fix 4 0 1 0
	fix 5 0 1 0

#######################################################################
#          Define Section Properties and Elements                     #
#######################################################################

# Define GEOMETRY and LOADING parameters -----------------------------
	set HCol [expr 210.*$mm];     # Column depth
	set BCol [expr 210.*$mm];     # Column width
	set BBeam [expr 360.*$mm];    # Beam width
	set HBeam [expr 180.*$mm];    # Beam depth
	set ABeam [expr $BBeam*$HBeam];# Beam area
	set Dy [expr 34.*$mm];        # Predicted yield displacement

# calculated parameters
	set ACol [expr $HCol*$BCol];        # Column cross-sectional area
	set ABeam [expr $BBeam*$HBeam];     # Beam cross-sectional area
	set IzCol [expr 1./12.*$BCol*pow($HCol,3)];
	set IzBeam [expr 1./12.*$BBeam*pow($HBeam,3)];
	set fc [expr 24.9*$MPa];      # 28 day concrete strength
	set EConc [expr 23700*$MPa];  # ACI Code concrete elastic modulus

# set up geometric transformations of element
	set PDeltaTransf 1;
	geomTransf PDelta $PDeltaTransf;    # PDelta transformation

# define rotational spring material,     assign the joint behavior to
the springs
	# matID Ke Mypos Myneg tetp tetpc McMy
	IbarraMat 1 1451.4 32.0 -40.0 0.044 0.087 1.22; # IL wide-beam
spring material
	IbarraMat 2 1344.5 32.4 -32.4 0.034 0.034 1.21; # IL column
spring material
	IbarraMat 3 1028.4 25.2 -25.2 0.024 0.032 1.20; # IL column
spring material

# define elastic beam and column elements using "element" command
	# command: element elasticBeamColumn $eleID $iNode $jNode $A $E
$I $transfID
	element elasticBeamColumn  1 1 21 $ACol $EConc $IzCol
$PDeltaTransf;    # column lower
```

```
      element elasticBeamColumn  2 23 3 $ACol $EConc $IzCol
$PDeltaTransf;    # column upper
      element elasticBeamColumn  3 24 4 $ABeam $EConc $IzBeam
$PDeltaTransf;    # beam right-hand side
      element elasticBeamColumn  4 25 5 $ABeam $EConc $IzBeam
$PDeltaTransf;    # beam left-hand side

# define zero length elements for rotational springs
      #rotSpring2D 12 1 12 2
      rotSpring2D 21 2 21 2
      rotSpring2D 23 2 23 3
      rotSpring2D 24 2 24 1
      rotSpring2D 25 2 25 1

# display the model with the node numbers
      DisplayModel2D NodeNumbers

######################################################################
#               Gravity Loads & Gravity Analysis                     #
######################################################################
# apply gravity loads
      #command: pattern PatternType $PatternID TimeSeriesType
      pattern Plain 101 Constant {
            # point loads on column nodes
            set P_F2 $PCol;
            load 3 0.0 $P_F2 0.0;
      }

# Gravity-analysis: load-controlled static analysis
      set Tol 1.0e-6;          # convergence tolerance for test
      constraints Plain;       # how it handles boundary conditions
      numberer RCM;            # renumber dof's to minimize band-width
      system BandGeneral;
      test NormDispIncr $Tol 6;
      algorithm Newton;
      set NstepGravity 10;     # apply gravity in 10 steps
      set DGravity [expr 1.0/$NstepGravity];    # load increment
      integrator LoadControl $DGravity;
      analysis Static;
      analyze $NstepGravity;
      loadConst -time 0.0
      puts "Model Built"

######################################################################
#               Recorders                                            #
######################################################################

# record top diplacement
      recorder Node -file $dataDir/JointDispPush.out -time -node 3 -
dof 1 disp;

# record applied force
      recorder Element -file  $dataDir/AppliedForcePush.out -ele 2
globalForce;
```

```
#####################################################################
#                                                                   #
#                         Analysis Section                          #
#                                                                   #
#####################################################################

#####################################################################
#                         Pushover Analysis                         #
#####################################################################

if {$analysisType == "pushover"} {
      puts "Running Pushover Analysis..."
      set lat2 1;
      pattern Plain 200 Linear {
            load 3 $lat2 0.0 0.0;
      }
# displacement parameters
      set IDctrlNode 3; # node where disp is read for disp control
      set IDctrlDOF 1;  # degree of freedom read for disp control
      set Dmax [expr 10.0*$Dy];      # maximum displacement of pushover
      set Dincr [expr 0.0005*$Dy];  # displacement increment

# analysis commands
      constraints Plain;
      numberer RCM;
      system BandGeneral;
      test NormUnbalance 1.0e-6 400;
      algorithm Newton;
      integrator DisplacementControl  $IDctrlNode   $IDctrlDOF $Dincr;
      analysis Static;
      set Nsteps [expr int($Dmax/$Dincr
      set ok [analyze $Nsteps];
      puts "Pushover complete";
}

#####################################################################
#               Cyclic Analysis                                     #
#####################################################################

if {$analysisType == "cyclic"} {
      puts "Running Cyclic Analysis..."
      set lat2 1;
      pattern Plain 200 Linear {
            load 3 -$lat2 0.0 0.0;
      }
# display deformed shape:
      set ViewScale 5;
      #DisplayModel2D DeformedShape $ViewScale ;

      # we need to set up parameters that are particular to the model.
      set IDctrlNode 3;
      set IDctrlDOF 1;
      set iDmax "0.5  0.75 1.0 1.5 2.0 3.0 4.0";
      set Dincr [expr 0.01*$Dy];
      set Fact $Dy;
      set CycleType Full;
      set Ncycles 3;
```

```
# ----------- set up analysis parameters
      source LibAnalysisStaticParameters.tcl;

#  ----------- perform Static Cyclic Displacements Analysis
      source GeneratePeaks.tcl
      set fmt1 "%s Cyclic analysis: CtrlNode %.1i, dof %.1i, Disp=%.3f
%s";  # format for screen/file output of DONE/PROBLEM analysis
      foreach Dmax $iDmax {
            set iDstep [GeneratePeaks $Dmax $Dincr $CycleType $Fact];
      # this proc is defined above
            for {set i 1} {$i <= $Ncycles} {incr i 1} {
                  set zeroD 0
                  set D0 0.0
                  foreach Dstep $iDstep {
                        set D1 $Dstep
                        set Dincr [expr $D1 - $D0]
                        integrator DisplacementControl  $IDctrlNode
$IDctrlDOF $Dincr
                        analysis Static
                        # --------first analyze command----------------
                        set ok [analyze 1]
                        # ----------if convergence failure-------------
                        if {$ok != 0} {
                        # if analysis fails, we try some other stuff
                              if {$ok != 0} {
                              puts "Trying Newton with Initial Tangent"
                                    test NormDispIncr   $Tol 2000 0
                                    algorithm Newton -initial
                                    set ok [analyze 1]
                                    test $testTypeStatic $TolStatic
$maxNumIterStatic    0
                                    algorithm $algorithmTypeStatic
                              }
                              if {$ok != 0} {
                                    puts "Trying Broyden .."
                                    algorithm Broyden 8
                                    set ok [analyze 1 ]
                                    algorithm $algorithmTypeStatic
                              }
                              if {$ok != 0} {
                                    puts "Trying NewtonWithLineSearch
.."
                                    algorithm NewtonLineSearch 0.8
                                    set ok [analyze 1]
                                    algorithm $algorithmTypeStatic
                              }
                              if {$ok != 0} {
                                    set putout [format $fmt1 "PROBLEM"
$IDctrlNode $IDctrlDOF [nodeDisp $IDctrlNode $IDctrlDOF] $LunitTXT]
                                    puts $putout
                                    return -1
                              }; # end if
                        }; # end if
                        # ----------------------------------
                        set D0 $D1; # move to next step
                  }; # end Dstep
            };    # end i
      };    # end of iDmaxCycl
```

```
	# ---------------------------------------------------------------
	if {$ok != 0 } {
		puts [format $fmt1 "PROBLEM" $IDctrlNode $IDctrlDOF
[nodeDisp $IDctrlNode $IDctrlDOF] $LunitTXT]
	} else {
		puts "CYCLIC ANALYSIS COMPLETED."
	}
}

########################################################################
#                  Time History/Dynamic Analysis                       #
########################################################################

if {$analysisType == "dynamic"} {
	puts "Running dynamic analysis..."
	# display deformed shape:
	set ViewScale 5;  # amplify display of deformed shape
	DisplayModel2D DeformedShape $ViewScale; # display deformed
shape, the scaling factor needs to be adjusted for each model

	# Rayleigh Damping
	set zeta 0.02;
	set a0 [expr $zeta*2.0*$w1*$w2/($w1 + $w2)];
	set a1 [expr $zeta*2.0/($w1 + $w2)];
	set a1_mod [expr $a1*(1.0+$n)/$n];
	region 4 -eleRange 111 222 -rayleigh 0.0 0.0 $a1_mod 0.0;
	region 5 -node 12 13 22 23 -rayleigh $a0 0.0 0.0 0.0;

	# define ground motion parameters
	set patternID 1;		# load pattern ID
	set GMdirection 1;		# ground motion direction (1 = x)
	set GMfile "NR94cnp.tcl";	# ground motion filename
	set dt 0.01;			# timestep of input GM file
	set Scalefact 1.0;		# ground motion scaling factor
	set TotalNumberOfSteps 2495;	# number of steps in ground motion
	set GMtime [expr $dt*$TotalNumberOfSteps + 10.0];
	set accelSeries "Series -dt $dt -filePath $GMfile -factor [expr
$Scalefact*$g]";
	pattern UniformExcitation $patternID $GMdirection -accel
$accelSeries;

	# define dynamic analysis parameters
	set dt_analysis 0.001;		# timestep of analysis
	wipeAnalysis;
	constraints Plain;
	numberer RCM;
	system UmfPack;
	test NormDispIncr 1.0e-8 50;
	algorithm NewtonLineSearch;
	integrator Newmark 0.5 0.25;
	analysis Transient;
	set NumSteps [expr round(($GMtime + 0.0)/$dt_analysis)];
```

```
	# perform the dynamic analysis and display whether analysis was
successful
		set ok [analyze $NumSteps $dt_analysis]; # ok = 0 if
analysis was completed
		if {$ok == 0} {
			puts "Dynamic analysis complete";
		} else {
			puts "Dynamic analysis did not converge";
		}
		# output time at end of analysis
		set currentTime [getTime];
		puts "The current time is: $currentTime";
		wipe all;
}
wipe all;


# GENERATE PEAKS PROCEDURE
# The procedure generates peaks for cyclic pushover

proc GeneratePeaks {Dmax {DincrStatic 0.01} {CycleType "Full"} {Fact
1} } {;
	file mkdir data
	set outFileID [open data/tmpDsteps.tcl w]
	set Disp 0.
	puts $outFileID "set iDstep { ";puts $outFileID $Disp;puts
$outFileID $Disp; # open vector definition and some 0
	set Dmax [expr $Dmax*$Fact];  # scale value
	if {$Dmax<0} {;  # avoid the divide by zero
		set dx [expr -$DincrStatic]
	} else {
		set dx $DincrStatic;
	}
	set NstepsPeak [expr int(abs($Dmax)/$DincrStatic)]
	for {set i 1} {$i <= $NstepsPeak} {incr i 1} {;
	set Disp [expr $Disp + $dx]
	puts $outFileID $Disp;
	}
	if {$CycleType !="Push"} {
		for {set i 1} {$i <= $NstepsPeak} {incr i 1} {;
		set Disp [expr $Disp - $dx]
		puts $outFileID $Disp;
		if {$CycleType !="Half"} {
			for {set i 1} {$i <= $NstepsPeak} {incr i 1} {;
				set Disp [expr $Disp - $dx]
				puts $outFileID $Disp;
	}
			for {set i 1} {$i <= $NstepsPeak} {incr i 1} {;
				set Disp [expr $Disp + $dx]
				puts $outFileID $Disp;
			}
		}
	}
	puts $outFileID " }";
	close $outFileID
	source data/tmpDsteps.tcl;
	return $iDstep
}
```

```
# -------------------------------------------------------------------------
# Wide Beam Column Joint Behavior Kulkarni IWB1
# With Ibarra-Krawinkler Deterioration Model
# ENES KARAASLAN

#########################################################################
#          Set Up & Source Definition                                   #
#########################################################################
      wipe all;
      model BasicBuilder -ndm 2 -ndf 3;
      source units.tcl
      source IbarraMatIL.tcl
      source rotSpring2D.tcl
      source DisplayModel2D.tcl
      source DisplayPlane.tcl

#########################################################################
#          Define Analysis Type                                         #
#########################################################################

# Define type of analysis:  "pushover" = pushover;  "dynamic" =
dynamic

      set analysisType "cyclic";
      if {$analysisType == "pushover"} {
            set dataDir Concentrated-Pushover-Output;
            file mkdir $dataDir;
      }
      if {$analysisType == "cyclic"} {
            set dataDir Concentrated-Cyclic-Output;
            file mkdir $dataDir;
      }
      if {$analysisType == "dynamic"} {
            set dataDir Concentrated-Dynamic-Output;
            file mkdir $dataDir;
      }

#########################################################################
#          Define Building Geometry, Nodes, and Constraints             #
#########################################################################

# define nodal masses and forces
      set PCol [expr 175.*$KN];
      set NodalMass [expr ($PCol)/$g];
      set Negligible 1e-9;
      set LCol [expr 1203.*$mm];
      set LBeam [expr 1880.*$mm];
      set HCol [expr 900.*$mm];
      set BCol [expr 300.*$mm];
      set BBeam [expr 800.*$mm];
      set HBeam [expr 300.*$mm];
      set ABeam [expr $BBeam*$HBeam];
      set Dy [expr 19.9*$mm];
```

```
# define nodes and assign masses to the beam-column joint
node 1 0. 0.;
node 2 0. [expr 1.0*$LCol] -mass $NodalMass $Negligible $Negligible;
node 3 0. [expr 2.0*$LCol]
node 4 $LBeam [expr 1.0*$LCol]
# define extra nodes for plastic hinge rotational springs
node 21 0. [expr $LCol]
node 23 0. [expr $LCol]
node 24 0. [expr $LCol]

# assign boundary condidtions
fix 1 1 1 0;
fix 4 0 1 0

######################################################################
#          Define Section Properties and Elements                    #
######################################################################

# Define GEOMETRY and LOADING parameters -----------------------------

# calculated parameters
set ACol [expr $HCol*$BCol];
set ABeam [expr $BBeam*$HBeam];
set IzCol [expr 1.0/12.*$BCol*pow($HCol,3)];
set IzBeam [expr 1./12.*$BBeam*pow($HBeam,3)];
set fc [expr 64.3*$MPa];
set EConc [expr 39500*$MPa];       # TS-500-2000 E=9500*(fc+8)^1/3

# set up geometric transformations of element
set PDeltaTransf 1;
geomTransf PDelta $PDeltaTransf;    # PDelta transformation

# define rotational spring material,
# matID Ke Mypos Myneg tetp tetpc McMy
IbarraMat 1 70479.8 345.3 -365.9 0.045 0.055 1.20;
IbarraMat 2 82354.9 560.0 -560.0 0.069 0.074 1.21;

# define elastic beam and column elements using "element" command
element elasticBeamColumn  1 1 21 $ACol $EConc $IzCol $PdeltaTransf
element elasticBeamColumn  2 23 3 $ACol $EConc $IzCol $PDeltaTransf;
element elasticBeamColumn  3 24 4 $ABeam $EConc $IzBeam $PDeltaTransf;

# define zero length elements for rotational springs
rotSpring2D 21 2 21 2
rotSpring2D 23 2 23 2
rotSpring2D 24 2 24 1
```

```
########################################################################
#               Gravity Loads & Gravity Analysis                       #
########################################################################
# apply gravity loads
      #command: pattern PatternType $PatternID TimeSeriesType
      pattern Plain 101 Constant {
            # point loads on column nodes
            set P_F2 $PCol;
            load 3 0.0 $P_F2 0.0;
      }

# Gravity-analysis: load-controlled static analysis
      set Tol 1.0e-6;           # convergence tolerance for test
      constraints Plain;        # how it handles boundary conditions
      numberer RCM;             # renumber dof's to minimize band-width
      system BandGeneral;       # how to store and solve the system of
equations in the analysis
      test NormDispIncr $Tol 6;
      algorithm Newton;
      set NstepGravity 10;
      set DGravity [expr 1.0/$NstepGravity];
      integrator LoadControl $DGravity;
      analysis Static;
      analyze $NstepGravity;
      loadConst -time 0.0
      puts "Model Built"


########################################################################
#               Recorders                                              #
########################################################################

if {$analysisType == "cyclic"} {
# record top diplacement
      recorder Node -file $dataDir/JointDispCyc.out -time -node 3 -dof
1 disp;
# record applied force
      recorder Element -file  $dataDir/AppliedForceCyc.out -ele 2
globalForce;
}
if {$analysisType == "pushover"} {
# record top diplacement
      recorder Node -file $dataDir/JointDispPush.out -time -node 3 -
dof 1 disp;
# record applied force
      recorder Element -file  $dataDir/AppliedForcePush.out -ele 2
globalForce;
}
if {$analysisType == "dynamic"} {
# record top diplacement
      recorder Node -file $dataDir/JointDispDyn.out -time -node 3 -dof
1 disp;
# record applied force
      recorder Element -file  $dataDir/AppliedForceDyn.out -ele 2
globalForce;
}
```

```
######################################################################
#                                                                    #
#                              Analysis Section                      #
#                                                                    #
######################################################################

######################################################################
#                             Pushover Analysis                      #
######################################################################

if {$analysisType == "pushover"} {
	puts "Running Pushover Analysis..."
	set lat2 1;
	pattern Plain 200 Linear {
		load 3 $lat2 0.0 0.0;
	}
	set IDctrlNode 3;
	set IDctrlDOF 1;
	set Dmax [expr 5.0*$Dy];
	set Dincr [expr 0.0005*$Dy];
	constraints Plain;
	numberer RCM;
	system BandGeneral;
	test NormUnbalance 1.0e-6 400;
	algorithm Newton;
	integrator DisplacementControl  $IDctrlNode   $IDctrlDOF $Dincr;
	analysis Static;
	set Nsteps [expr int($Dmax/$Dincr)];
	set ok [analyze $Nsteps];
	puts "Pushover complete";
}

######################################################################
#              Cyclic Analysis                                       #
######################################################################

if {$analysisType == "cyclic"} {
	puts "Running Cyclic Analysis..."
# assign lateral loads and create load pattern:  Displacement is
applied.
	set lat2 1; # a small force applied to prevent convergence
errors.
	pattern Plain 200 Linear {
		load 3 -$lat2 0.0 0.0;
	}
# display deformed shape:
	set ViewScale 5;
	#DisplayModel2D DeformedShape $ViewScale ;	# display
deformed shape, the scaling factor needs to be adjusted for each model
# -----------------------------------------------------------------
------------------------------

	# we need to set up parameters that are particular to the model.
	set IDctrlNode 3;		# node where displacement is read
for displacement control
	set IDctrlDOF 1;		# degree of freedom of displacement
read for displacement control
	# characteristics of pushover analysis
```

```
	set iDmax "0.5  0.75 1.0 1.5 2.0 3.0 4.0 5.0"; # vector of displacement-cycle peaks, in terms of expected yield displacement
	set Dincr [expr 0.01*$Dy];				# displacement increment for pushover.
	set Fact $Dy;				# scale drift ratio by expected yield displacement for displacement cycles
	set CycleType Full;			# you can do Full / Push / Half cycles with the proc
	set Ncycles 3;				# specify the number of cycles at each peak

# ----------- set up analysis parameters
	source LibAnalysisStaticParameters.tcl;	# constraintsHandler,DOFnumberer,system-ofequations,convergenceTest,solutionAlgorithm,integrator

#  ---------------------------------    perform Static Cyclic Displacements Analysis
	source GeneratePeaks.tcl
	set fmt1 "%s Cyclic analysis: CtrlNode %.1i, dof %.1i, Disp=%.3f %s";	# format for screen/file output of DONE/PROBLEM analysis
	foreach Dmax $iDmax {
		set iDstep [GeneratePeaks $Dmax $Dincr $CycleType $Fact];	# this proc is defined above
		for {set i 1} {$i <= $Ncycles} {incr i 1} {
			set zeroD 0
			set D0 0.0
			foreach Dstep $iDstep {
				set D1 $Dstep
				set Dincr [expr $D1 - $D0]
				integrator DisplacementControl  $IDctrlNode $IDctrlDOF $Dincr
				analysis Static
				# ---------------------------------------------first analyze command------------------------
				set ok [analyze 1]
				# ---------------------------------------------if convergence failure-------------------------
				if {$ok != 0} {
					# if analysis fails, we try some other stuff
					# performance is slower inside this loop
	global maxNumIterStatic;	    # max no. of iterations performed before "failure to converge" is ret'd
					if {$ok != 0} {
						puts "Trying Newton with Initial Tangent .."
						test NormDispIncr   $Tol 2000 0
						algorithm Newton -initial
						set ok [analyze 1]
						test $testTypeStatic $TolStatic $maxNumIterStatic    0
						algorithm $algorithmTypeStatic
					}
					if {$ok != 0} {
						puts "Trying Broyden .."
						algorithm Broyden 8
						set ok [analyze 1 ]
```

```
                                        algorithm $algorithmTypeStatic
                                }
                                if {$ok != 0} {
                                        puts "Trying NewtonWithLineSearch"
                                        algorithm NewtonLineSearch 0.8
                                        set ok [analyze 1]
                                        algorithm $algorithmTypeStatic
                                }
                                if {$ok != 0} {
                                        set putout [format $fmt1 "PROBLEM"
$IDctrlNode $IDctrlDOF [nodeDisp $IDctrlNode $IDctrlDOF] $LunitTXT]
                                        puts $putout
                                        return -1
                                }; # end if
                        }; # end if
                        # ---------------------------------------------
                        set D0 $D1;             # move to next step
                }; # end Dstep
        };      # end i
};      # end of iDmaxCycl
# -----------------------------------------------------------------
if {$ok != 0 } {
        puts [format $fmt1 "PROBLEM" $IDctrlNode $IDctrlDOF
[nodeDisp $IDctrlNode $IDctrlDOF] $LunitTXT]
} else {
        puts "CYCLIC ANALYSIS COMPLETED."
}
}

######################################################################
#   Time History/Dynamic Analysis                                    #
######################################################################

if {$analysisType == "dynamic"} {
        puts "Running dynamic analysis..."
        # display deformed shape:
        set ViewScale 5;  # amplify display of deformed shape
        DisplayModel2D DeformedShape $ViewScale;

        # Rayleigh Damping
        set zeta 0.02;
        set a0 [expr $zeta*2.0*$w1*$w2/($w1 + $w2)];
        set a1 [expr $zeta*2.0/($w1 + $w2)];
        set a1_mod [expr $a1*(1.0+$n)/$n];
        region 4 -eleRange 111 222 -rayleigh 0.0 0.0 $a1_mod 0.0;
        region 5 -node 12 13 22 23 -rayleigh $a0 0.0 0.0 0.0;

        # define ground motion parameters
        set patternID 1;
        set GMdirection 1;
        set GMfile "NR94cnp.tcl";
        set dt 0.01;
        set Scalefact 1.0;
        set TotalNumberOfSteps 2495;
        set GMtime [expr $dt*$TotalNumberOfSteps + 10.0];
        set accelSeries "Series -dt $dt -filePath $GMfile -factor [expr
$Scalefact*$g]";
```

```
	pattern UniformExcitation $patternID $GMdirection -accel
$accelSeries;

	# define dynamic analysis parameters
	set dt_analysis 0.001;
	wipeAnalysis;
	constraints Plain;
	numberer RCM;
	system UmfPack;
	test NormDispIncr 1.0e-8 50;
	algorithm NewtonLineSearch;
	integrator Newmark 0.5 0.25;
	analysis Transient;
	set NumSteps [expr round(($GMtime + 0.0)/$dt_analysis)];
	set ok [analyze $NumSteps $dt_analysis];
		if {$ok == 0} {
			puts "Dynamic analysis complete";
		} else {
			puts "Dynamic analysis did not converge";
		}

	set currentTime [getTime];
	puts "The current time is: $currentTime";
	wipe all;
}

wipe all;
```

B.3. OpenSees Code Files for Real Wide Beam Building

```
# ----------------------------------------------------------------------
# REAL 2D WIDE BEAM STRUCTURE BUILDING 5-story, 3-bay
# With Ibarra-Krawinkler Deterioration Model Defined at Springs
# PREPARED BY ENES KARAASLAN

######################################################################
#          Set Up & Source Definition
######################################################################
wipe all;                 # clear memory of past model definitions
model BasicBuilder -ndm 2 -ndf 3;
source units.tcl
source calibration.tcl
source rotSpring2D.tcl
source DisplayModel2D.tcl
source DisplayPlane.tcl

######################################################################
#          Define Analysis Type                                      #
######################################################################

# Define type of analysis:  "pushover" = pushover; "dynamic" = dynamic

set analysisType "dynamic";

if {$analysisType == "static"} {
      set dataDir Concentrated-Static-Output;   # name of output folder
      file mkdir $dataDir;                      # create output folder
}
if {$analysisType == "pushover"} {
      set dataDir Concentrated-Pushover-Output; # name of output folder
      file mkdir $dataDir;                      # create output folder
}
if {$analysisType == "cyclic"} {
      set dataDir Concentrated-Cyclic-Output;   # name of output folder
      file mkdir $dataDir;                      # create output folder
}
if {$analysisType == "dynamic"} {
      set dataDir Concentrated-Dynamic-Output;  # name of output folder
      file mkdir $dataDir;                      # create output folder
      }

######################################################################
#          Define Building Geometry, Nodes, and Constraints          #
######################################################################

# define structure-geometry parameters
set NStories 5;                # number of stories
set NBays 4;                   # number of frame bays
set WBay      [expr 6.*$m];    # bay width
set HStory1   [expr 4.*$m];    # 1st story height
set HStoryTyp [expr 3.*$m];    # story height of other stories
set HBuilding [expr $HStory1 + ($NStories-1)*$HStoryTyp];
```

```
# calculate locations of beam/column joints:
set Pier1 0.0;                          # leftmost column line
set Pier2 [expr $Pier1 + $WBay];
set Pier3 [expr $Pier2 + $WBay];
set Pier4 [expr $Pier3 + $WBay];
set Pier5 [expr $Pier4 + $WBay];    # rightmost column line
set FloorBase 0.0;                      # ground floor
set Floor1 [expr $FloorBase + $HStory1];
set Floor2 [expr $Floor1 + $HStoryTyp];
set Floor3 [expr $Floor2 + $HStoryTyp];
set Floor4 [expr $Floor3 + $HStoryTyp];
set Floor5 [expr $Floor4 + $HStoryTyp];

# calculate nodal masses -- lump floor masses at frame nodes
set Floor1Weight [expr 1054.*$KN];        # weight of Floor 1
set Floor2Weight [expr 1034.*$KN];        # weight of Floor 2
set Floor3Weight [expr 1034.*$KN];        # weight of Floor 3
set Floor4Weight [expr 1034.*$KN];        # weight of Floor 4
set Floor5Weight [expr 1034.*$KN];        # weight of Floor 5
set WBuilding  [expr $Floor1Weight+$Floor2Weight + $Floor3Weight +
$Floor4Weight + $Floor5Weight];# total building weight
set NodalMass1ex [expr ($Floor1Weight/$g) / (8.0)];  # mass at each
exterior node on Floor 1
set NodalMass1in [expr ($Floor1Weight/$g) / (4.0)];  # mass at each
interior node on Floor 1
set NodalMass2ex [expr ($Floor2Weight/$g) / (8.0)];  # mass at each
exterior node on Floor 2
set NodalMass2in [expr ($Floor2Weight/$g) / (4.0)];  # mass at each
interior node on Floor 2
set NodalMass3ex [expr ($Floor3Weight/$g) / (8.0)];  # mass at each
exterior node on Floor 3
set NodalMass3in [expr ($Floor3Weight/$g) / (4.0)];  # mass at each
interior node on Floor 3
set NodalMass4ex [expr ($Floor4Weight/$g) / (8.0)];  # mass at each
exterior node on Floor 4
set NodalMass4in [expr ($Floor4Weight/$g) / (4.0)];  # mass at each
interior node on Floor 4
set NodalMass5ex [expr ($Floor5Weight/$g) / (8.0)];  # mass at each
exterior node on Floor 5
set NodalMass5in [expr ($Floor5Weight/$g) / (4.0)];  # mass at each
interior node on Floor 5

#Axial load levels on single piers at each Floor
set AxialLoadP1 [expr $WBuilding/5.0];
set AxialLoadP2 [expr
($Floor2Weight+$Floor3Weight+$Floor4Weight+$Floor5Weight)/5.0];
set AxialLoadP3 [expr
($Floor3Weight+$Floor4Weight+$Floor5Weight)/5.0];
set AxialLoadP4 [expr ($Floor4Weight+$Floor5Weight)/5.0];
set AxialLoadP5 [expr ($Floor5Weight)/5.0];
set BeamAxialLoad [expr 50.*$KN];

#Small number definition
set Negligible 1e-9;
```

```
# define nodes and assign masses to beam-column intersections of frame
# nodeID convention:  "xy" where x = Pier # and y = Floor #
node 10 $Pier1 $FloorBase;
node 20 $Pier2 $FloorBase;
node 30 $Pier3 $FloorBase;
node 40 $Pier4 $FloorBase;
node 50 $Pier5 $FloorBase;
node 11 $Pier1 $Floor1 -mass $NodalMass1ex $Negligible $Negligible;
node 21 $Pier2 $Floor1 -mass $NodalMass1in $Negligible $Negligible;
node 31 $Pier3 $Floor1 -mass $NodalMass1in $Negligible $Negligible;
node 41 $Pier4 $Floor1 -mass $NodalMass1in $Negligible $Negligible;
node 51 $Pier5 $Floor1 -mass $NodalMass1ex $Negligible $Negligible;
node 12 $Pier1 $Floor2 -mass $NodalMass2ex $Negligible $Negligible;
node 22 $Pier2 $Floor2 -mass $NodalMass2in $Negligible $Negligible;
node 32 $Pier3 $Floor2 -mass $NodalMass2in $Negligible $Negligible;
node 42 $Pier4 $Floor2 -mass $NodalMass2in $Negligible $Negligible;
node 52 $Pier5 $Floor2 -mass $NodalMass2ex $Negligible $Negligible;
node 13 $Pier1 $Floor3 -mass $NodalMass3ex $Negligible $Negligible;
node 23 $Pier2 $Floor3 -mass $NodalMass3in $Negligible $Negligible;
node 33 $Pier3 $Floor3 -mass $NodalMass3in $Negligible $Negligible;
node 43 $Pier4 $Floor3 -mass $NodalMass3in $Negligible $Negligible;
node 53 $Pier5 $Floor3 -mass $NodalMass3ex $Negligible $Negligible;
node 14 $Pier1 $Floor4 -mass $NodalMass4ex $Negligible $Negligible;
node 24 $Pier2 $Floor4 -mass $NodalMass4in $Negligible $Negligible;
node 34 $Pier3 $Floor4 -mass $NodalMass4in $Negligible $Negligible;
node 44 $Pier4 $Floor4 -mass $NodalMass4in $Negligible $Negligible;
node 54 $Pier5 $Floor4 -mass $NodalMass4ex $Negligible $Negligible;
node 15 $Pier1 $Floor5 -mass $NodalMass5ex $Negligible $Negligible;
node 25 $Pier2 $Floor5 -mass $NodalMass5in $Negligible $Negligible;
node 35 $Pier3 $Floor5 -mass $NodalMass5in $Negligible $Negligible;
node 45 $Pier4 $Floor5 -mass $NodalMass5in $Negligible $Negligible;
node 55 $Pier5 $Floor5 -mass $NodalMass5ex $Negligible $Negligible;

# define extra nodes for plastic hinge rotational springs
      # "a" convention: 4 = left; 5 = right;
      # "a" convention: 6 = below; 7 = above;

# hinges at the base
      node 107 $Pier1 $FloorBase;
      node 207 $Pier2 $FloorBase;
      node 307 $Pier3 $FloorBase;
      node 407 $Pier4 $FloorBase;
      node 507 $Pier5 $FloorBase;
# hinges at story 1
      node 116 $Pier1 $Floor1;
      node 216 $Pier2 $Floor1;
      node 316 $Pier3 $Floor1;
      node 416 $Pier4 $Floor1;
      node 516 $Pier5 $Floor1;
      node 115 $Pier1 $Floor1;
      node 215 $Pier2 $Floor1;
      node 315 $Pier3 $Floor1;
      node 415 $Pier4 $Floor1;
      node 117 $Pier1 $Floor1;
      node 217 $Pier2 $Floor1;
      node 317 $Pier3 $Floor1;
      node 417 $Pier4 $Floor1;
```

```
    node 517 $Pier5 $Floor1;
    node 214 $Pier2 $Floor1;
    node 314 $Pier3 $Floor1;
    node 414 $Pier4 $Floor1;
    node 514 $Pier5 $Floor1;
# hinges at story 2
    node 126 $Pier1 $Floor2;
    node 226 $Pier2 $Floor2;
    node 326 $Pier3 $Floor2;
    node 426 $Pier4 $Floor2;
    node 526 $Pier5 $Floor2;
    node 125 $Pier1 $Floor2;
    node 225 $Pier2 $Floor2;
    node 325 $Pier3 $Floor2;
    node 425 $Pier4 $Floor2;
    node 127 $Pier1 $Floor2;
    node 227 $Pier2 $Floor2;
    node 327 $Pier3 $Floor2;
    node 427 $Pier4 $Floor2;
    node 527 $Pier5 $Floor2;
    node 224 $Pier2 $Floor2;
    node 324 $Pier3 $Floor2;
    node 424 $Pier4 $Floor2;
    node 524 $Pier5 $Floor2;
# hinges at story 3
    node 136 $Pier1 $Floor3;
    node 236 $Pier2 $Floor3;
    node 336 $Pier3 $Floor3;
    node 436 $Pier4 $Floor3;
    node 536 $Pier5 $Floor3;
    node 135 $Pier1 $Floor3;
    node 235 $Pier2 $Floor3;
    node 335 $Pier3 $Floor3;
    node 435 $Pier4 $Floor3;
    node 137 $Pier1 $Floor3;
    node 237 $Pier2 $Floor3;
    node 337 $Pier3 $Floor3;
    node 437 $Pier4 $Floor3;
    node 537 $Pier5 $Floor3;
    node 234 $Pier2 $Floor3;
    node 334 $Pier3 $Floor3;
    node 434 $Pier4 $Floor3;
    node 534 $Pier5 $Floor3;
# hinges at Story 4
    node 146 $Pier1 $Floor4;
    node 246 $Pier2 $Floor4;
    node 346 $Pier3 $Floor4;
    node 446 $Pier4 $Floor4;
    node 546 $Pier5 $Floor4;
    node 145 $Pier1 $Floor4;
    node 245 $Pier2 $Floor4;
    node 345 $Pier3 $Floor4;
    node 445 $Pier4 $Floor4;
    node 147 $Pier1 $Floor4;
    node 247 $Pier2 $Floor4;
    node 347 $Pier3 $Floor4;
    node 447 $Pier4 $Floor4;
    node 547 $Pier5 $Floor4;
```

```
      node 244 $Pier2 $Floor4;
      node 344 $Pier3 $Floor4;
      node 444 $Pier4 $Floor4;
      node 544 $Pier5 $Floor4;
# hinges at Story 5
      node 156 $Pier1 $Floor5;
      node 256 $Pier2 $Floor5;
      node 356 $Pier3 $Floor5;
      node 456 $Pier4 $Floor5;
      node 556 $Pier5 $Floor5;
      node 155 $Pier1 $Floor5;
      node 255 $Pier2 $Floor5;
      node 355 $Pier3 $Floor5;
      node 455 $Pier4 $Floor5;
      node 254 $Pier2 $Floor5;
      node 354 $Pier3 $Floor5;
      node 454 $Pier4 $Floor5;
      node 554 $Pier5 $Floor5;
# assign boundary conditions
      fix 10 1 1 1;
      fix 20 1 1 1;
      fix 30 1 1 1;
      fix 40 1 1 1;
      fix 50 1 1 1;


######################################################################
#                                                                    #
#        Define Section Properties, Materials and Elements           #
#                                                                    #
######################################################################

# Define Section GEOMETRY parameters ---------------------------------
set HCol  [expr 600.*$mm];           # Column depth
set BCol  [expr 300.*$mm];           # Column width
set BBeam [expr 500.*$mm];           # Beam width
set HBeam [expr 320.*$mm];           # Beam depth
set ABeam [expr $BBeam*$HBeam];      # Beam area
set HCover [expr 25.*$mm];           # Cover concrete depth
set ACol  [expr $HCol*$BCol];        # Column cross-sectional area
set ABeam [expr $BBeam*$HBeam];      # Beam cross-sectional area
set IzCol  [expr 1./12.*$BCol*pow($HCol,3)]; # Column moment of inertia
set IzCol2  [expr 1./12.*$HCol*pow($BCol,3)];# Column moment of inertia
rotated 90 degree
set IzBeam [expr 1./12.*$BBeam*pow($HBeam,3)];# Beam moment of inertia

# Reinforcement Parameters
#Column reinforcement
set CompStRatCol 0.01;  # Column Compression reinforcement ratio
set TenStRatCol 0.01;   # Column Tension reinforcement ratio
set ShrStRatCol 0.005;  # Column Shear reinforcement ratio
set CompStRatBeam 0.005; # Beam Compression reinforcement ratio
set TenStRatBeam 0.005;  # Beam Tension reinforcement ratio
set ShrStRatBeam 0.0025; # Beam Shear reinforcement ratio
# Other Material Parameters
set fc [expr 30.*$MPa];        #28 day concrete strength
set fy [expr 420.*$MPa];       #Steel yield strength
```

```
set EConc [expr 3250.*sqrt($fc*$MPa)+14000*$MPa];     #Elastic Modulus
of Concrete
set Esteel [expr 200000.*$MPa];     #Elastic Modulus of Steel
set EInf    [expr 3100.*$MPa];      #Elastic Modulus of Infill Panels

# Masonry Infill Parameters
set tInf [expr 0.15*$m];            #Thickness of the infill panel
set hw [expr $HStoryTyp-$HBeam]
set dInf [expr sqrt(pow($hw,2)+pow($WBay-$HCol,2))]; #Diagonal Length
of Infill panel
set teta [expr atan(1.*($hw)/($WBay-$HCol))];  #Equivalent strut angle
set lamda [expr
$HStoryTyp*pow($EInf*$tInf*sin(2.*$teta)/4./$EConc/$IzCol/$hw,0.25)]
set WidthInf [expr 0.175*$dInf*pow($lamda,0.4)]; #Equivalent strut
width
set AInf [expr $WidthInf*$tInf];    #Equivalent strut area

# set up geometric transformations of element
      set PDeltaTransf 1;
      geomTransf PDelta $PDeltaTransf;    # PDelta transformation

# define rotational spring material,
# Define Column Springs
# mtag width depth cover fconc fsteel axial compr tens shear barslip
      CalibrationConvFrame 10 [expr 1.*$EConc/$MPa] [expr
1.*$Esteel/$MPa] [expr 1.*$BCol/$mm] [expr 1.*$HCol/$mm] [expr
1.*$HCover/$mm] [expr 1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr
1.*$AxialLoadP1/$KN] $CompStRatCol $TenStRatCol $ShrStRatCol 1;
#column springs at first floor
      Calibration 1 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa] [expr
1.*$BCol/$mm] [expr 1.*$HCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP1/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at first
floor
      Calibration 2 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa] [expr
1.*$BCol/$mm] [expr 1.*$HCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP2/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at second
floor
      Calibration 3 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa] [expr
1.*$BCol/$mm] [expr 1.*$HCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP3/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at third
floor
      Calibration 4 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa] [expr
1.*$BCol/$mm] [expr 1.*$HCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP4/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at forth
floor
      Calibration 5 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa] [expr
1.*$BCol/$mm] [expr 1.*$HCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP5/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at fifth
floor
# Rotated Column springs
      CalibrationConvFrame 101 [expr 1.*$EConc/$MPa] [expr
1.*$Esteel/$MPa] [expr 1.*$HCol/$mm] [expr 1.*$BCol/$mm] [expr
```

```
1.*$HCover/$mm] [expr 1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr
1.*$AxialLoadP1/$KN] $CompStRatCol $TenStRatCol $ShrStRatCol 1;

#column springs at first floor
	Calibration 11 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa]
[expr 1.*$HCol/$mm] [expr 1.*$BCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP1/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at first
floor
	Calibration 21 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa]
[expr 1.*$HCol/$mm] [expr 1.*$BCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP2/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at second
floor
	Calibration 31 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa]
[expr 1.*$HCol/$mm] [expr 1.*$BCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP3/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at third
floor
	Calibration 41 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa]
[expr 1.*$HCol/$mm] [expr 1.*$BCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP4/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at forth
floor
	Calibration 51 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa]
[expr 1.*$HCol/$mm] [expr 1.*$BCol/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$AxialLoadP5/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 1; #column springs at fifth
floor
#Define Beam Springs
# mtag width depth cover fconc fsteel axial compr tens shear barslip
	Calibration 6 [expr 1.*$EConc/$MPa] [expr 1.*$Esteel/$MPa] [expr
1.*$BBeam/$mm] [expr 1.*$HBeam/$mm] [expr 1.*$HCover/$mm] [expr
1.*$fc/$MPa] [expr 1.*$fy/$MPa] [expr 1.*$BeamAxialLoad/$KN]
$CompStRatCol $TenStRatCol $ShrStRatCol 0; #Beam springs

#Define material for masonry infill
source procUniaxialPinching.tcl
set pEnvelopeStress [list [expr 0.002*$MPa] [expr 0.004*$MPa] [expr
0.006*$MPa] [expr 0.001*$MPa]]
set nEnvelopeStress [list [expr -0.65*$MPa] [expr -0.75*$MPa] [expr -
1.*$MPa] [expr -0.25*$MPa]]
set pEnvelopeStrain [list 0.0005 0.0010 0.0025 0.4]
set nEnvelopeStrain [list -0.0005 -0.0010 -0.0025 -0.0125]
set rDisp [list 0.5 0.5]
set rForce [list 0.25 0.25]
set uForce [list 0.05 0.05]
set gammaK [list 1.0 0.2 0.3 0.2 0.9]
set gammaD [list 0.5 0.5 2.0 2.0 0.5]
set gammaF [list 1.0 0.0 1.0 1.0 0.9]
set gammaE 10
set dam "cycle"
procUniaxialPinching 7 $pEnvelopeStress $nEnvelopeStress
$pEnvelopeStrain $nEnvelopeStrain $rDisp $rForce $uForce $gammaK
$gammaD $gammaF $gammaE $dam
```

```
# define elastic beam and column elements using "element" command
# command: element elasticBeamColumn $eleID $iNode $jNode $A $E $I
$transfID
#First Story Column Elements
element elasticBeamColumn  1 107 116 $ACol $EConc $IzCol
$PDeltaTransf;    #Pier1
element elasticBeamColumn  2 207 216 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier2
element elasticBeamColumn  3 307 316 $ACol $EConc $IzCol
$PDeltaTransf; #Pier3
element elasticBeamColumn  4 407 416 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier4
element elasticBeamColumn  5 507 516 $ACol $EConc $IzCol
$PDeltaTransf;    #Pier5
#First Story Beam Elements
element elasticBeamColumn  6 115 214 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 1
element elasticBeamColumn  7 215 314 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 2
element elasticBeamColumn  8 315 414 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 3
element elasticBeamColumn  9 415 514 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 4
#Second Story Column Elements
element elasticBeamColumn  10 117 126 $ACol $EConc $IzCol
$PDeltaTransf; #Pier1
element elasticBeamColumn  11 217 226 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier2
element elasticBeamColumn  12 317 326 $ACol $EConc $IzCol
$PDeltaTransf; #Pier3
element elasticBeamColumn  13 417 426 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier4
element elasticBeamColumn  14 517 526 $ACol $EConc $IzCol
$PDeltaTransf; #Pier5
#Second Story Beam Elements
element elasticBeamColumn  15 125 224 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 1
element elasticBeamColumn  16 225 324 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 2
element elasticBeamColumn  17 325 424 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 3
element elasticBeamColumn  18 425 524 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 4
#Third Story Column Elements
element elasticBeamColumn  19 127 136 $ACol $EConc $IzCol
$PDeltaTransf; #Pier1
element elasticBeamColumn  20 227 236 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier2
element elasticBeamColumn  21 327 336 $ACol $EConc $IzCol
$PDeltaTransf; #Pier3
element elasticBeamColumn  22 427 436 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier4
element elasticBeamColumn  23 527 536 $ACol $EConc $IzCol
$PDeltaTransf; #Pier5
#Third Story Beam Elements
```

```
element elasticBeamColumn  24 135 234 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 1
element elasticBeamColumn  25 235 334 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 2
element elasticBeamColumn  26 335 434 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 3
element elasticBeamColumn  27 435 534 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 4
#Forth Story Column Elements
element elasticBeamColumn  28 137 146 $ACol $EConc $IzCol
$PDeltaTransf; #Pier1
element elasticBeamColumn  29 237 246 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier2
element elasticBeamColumn  30 337 346 $ACol $EConc $IzCol
$PDeltaTransf; #Pier3
element elasticBeamColumn  31 437 446 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier4
element elasticBeamColumn  32 537 546 $ACol $EConc $IzCol
$PDeltaTransf; #Pier5
#Forth Story Beam Elements
element elasticBeamColumn  33 145 244 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 1
element elasticBeamColumn  34 245 344 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 2
element elasticBeamColumn  35 345 444 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 3
element elasticBeamColumn  36 445 544 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 3
#Fifth Story Column Elements
element elasticBeamColumn  37 147 156 $ACol $EConc $IzCol
$PDeltaTransf; #Pier1
element elasticBeamColumn  38 247 256 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier2
element elasticBeamColumn  39 347 356 $ACol $EConc $IzCol
$PDeltaTransf; #Pier3
element elasticBeamColumn  40 447 456 $ACol $EConc $IzCol2
$PDeltaTransf;#Pier4
element elasticBeamColumn  41 547 556 $ACol $EConc $IzCol
$PDeltaTransf; #Pier5
#Fifth Story Beam Elements
element elasticBeamColumn  42 155 254 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 1
element elasticBeamColumn  43 255 354 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 2
element elasticBeamColumn  44 355 454 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 3
element elasticBeamColumn  45 455 554 $ABeam $EConc $IzBeam
$PDeltaTransf; #Bay 4

# Define equivalent masonry truss elements tag ndI ndJ A mattag
element truss 1221 12 21 $AInf 7
element truss 1322 13 22 $AInf 7
element truss 1423 14 23 $AInf 7
element truss 1524 15 24 $AInf 7
element truss 4251 42 51 $AInf 7
element truss 4352 43 52 $AInf 7
element truss 4453 44 53 $AInf 7
element truss 4554 45 54 $AInf 7
```

```
# Base Floor Springs
rotSpring2D 107 10 107 10; #node 10
rotSpring2D 207 20 207 101; #node 20
rotSpring2D 307 30 307 10; #node 30
rotSpring2D 407 40 407 101; #node 40
rotSpring2D 507 50 507 10; #node 50
# First Floor Springs
rotSpring2D 116 11 116 1; #node 11
rotSpring2D 216 21 216 11; #node 21
rotSpring2D 316 31 316 1; #node 31
rotSpring2D 416 41 416 11; #node 41
rotSpring2D 516 51 516 1; #node 51
rotSpring2D 117 11 117 2; #node 11
rotSpring2D 217 21 217 21; #node 21
rotSpring2D 317 31 317 2; #node 31
rotSpring2D 417 41 417 21; #node 41
rotSpring2D 517 51 517 2; #node 51
rotSpring2D 214 21 214 6; #node 21
rotSpring2D 314 31 314 6; #node 31
rotSpring2D 414 41 414 6; #node 41
rotSpring2D 514 51 514 6; #node 51
rotSpring2D 115 11 115 6; #node 11
rotSpring2D 215 21 215 6; #node 21
rotSpring2D 315 31 315 6; #node 31
rotSpring2D 415 41 415 6; #node 41
# Second Floor Springs
rotSpring2D 126 12 126 2; #node 12
rotSpring2D 226 22 226 21; #node 22
rotSpring2D 326 32 326 2; #node 32
rotSpring2D 426 42 426 21; #node 42
rotSpring2D 526 52 526 2; #node 52
rotSpring2D 127 12 127 3; #node 12
rotSpring2D 227 22 227 31; #node 22
rotSpring2D 327 32 327 3; #node 32
rotSpring2D 427 42 427 31; #node 42
rotSpring2D 527 52 527 3; #node 52
rotSpring2D 224 22 224 6; #node 22
rotSpring2D 324 32 324 6; #node 32
rotSpring2D 424 42 424 6; #node 42
rotSpring2D 524 52 524 6; #node 52
rotSpring2D 125 12 125 6; #node 12
rotSpring2D 225 22 225 6; #node 22
rotSpring2D 325 32 325 6; #node 32
rotSpring2D 425 42 425 6; #node 42
# Third Floor Springs
rotSpring2D 136 13 136 3; #node 13
rotSpring2D 236 23 236 31; #node 23
rotSpring2D 336 33 336 3; #node 33
rotSpring2D 436 43 436 31; #node 43
rotSpring2D 536 53 536 3; #node 53
rotSpring2D 137 13 137 4; #node 13
rotSpring2D 237 23 237 41; #node 23
rotSpring2D 337 33 337 4; #node 33
rotSpring2D 437 43 437 41; #node 43
rotSpring2D 537 53 537 4; #node 53
rotSpring2D 234 23 234 6; #node 23
```

```
rotSpring2D 334 33 334 6; #node 33
rotSpring2D 434 43 434 6; #node 43
rotSpring2D 534 53 534 6; #node 53
rotSpring2D 135 13 135 6; #node 13
rotSpring2D 235 23 235 6; #node 23
rotSpring2D 335 33 335 6; #node 33
rotSpring2D 435 43 435 6; #node 43
# Forth Floor Springs
rotSpring2D 146 14 146 4; #node 14
rotSpring2D 246 24 246 41; #node 24
rotSpring2D 346 34 346 4; #node 34
rotSpring2D 446 44 446 41; #node 44
rotSpring2D 546 54 546 4; #node 54
rotSpring2D 147 14 147 5; #node 14
rotSpring2D 247 24 247 51;#node 24
rotSpring2D 347 34 347 5; #node 34
rotSpring2D 447 44 447 51;#node 44
rotSpring2D 547 54 547 5; #node 54
rotSpring2D 244 24 244 6; #node 24
rotSpring2D 344 34 344 6; #node 34
rotSpring2D 444 44 444 6; #node 44
rotSpring2D 544 54 544 6; #node 54
rotSpring2D 145 14 145 6; #node 14
rotSpring2D 245 24 245 6; #node 24
rotSpring2D 345 34 345 6; #node 34
rotSpring2D 445 44 445 6; #node 44
# Fifth Floor Springs
rotSpring2D 156 15 156 5; #node 15
rotSpring2D 256 25 256 51;#node 25
rotSpring2D 356 35 356 5; #node 35
rotSpring2D 456 45 456 51;#node 45
rotSpring2D 556 55 556 5; #node 55
rotSpring2D 254 25 254 6; #node 25
rotSpring2D 354 35 354 6; #node 35
rotSpring2D 454 45 454 6; #node 45
rotSpring2D 554 55 554 6; #node 55
rotSpring2D 155 15 155 6; #node 15
rotSpring2D 255 25 255 6; #node 25
rotSpring2D 355 35 355 6; #node 35
rotSpring2D 455 45 455 6; #node 45

# display the model with the node numbers
DisplayModel2D NodeNumbers

# create region for springs nodes
#Base Floor
region 1 -ele 107 207 307 407 507;
#First Floor
region 2 -ele 116 216 316 416 516 117 217 317 417 517 214 314 414 514
115 215 315 415;
#Second Floor
region 3 -ele 126 226 326 426 526 127 227 327 427 527 224 324 424 524
125 225 325 425;
#Third Floor
region 4 -ele 136 236 336 436 536 137 237 337 437 537 234 334 434 534
135 235 335 435;
#Forth Floor
```

```
region 5 -ele 146 246 346 446 546 147 247 347 447 547 244 344 444 544
145 245 345 445;
#Fifth Floor
region 6 -ele 156 256 356 456 556 254 354 454 554 155 255 355 455;
#All Nodes
region 7 -ele 107 207 307 407 507 116 216 316 416 516 117 217 317 417
517 214 314 414 514 115 215 315 415 126 226 326 426 526 127 227 327
427 527 224 324 424 524 125 225 325 425 136 236 336 436 536 137 237
337 437 537 234 334 434 534 135 235 335 435 146 246 346 446 546 147
247 347 447 547 244 344 444 544 145 245 345 445 156 256 356 456 556
254 354 454 554 155 255 355 455;
puts "OKAY"

######################################################################
#                        Eigenvalue Analysis                         #
######################################################################

set pi [expr 2.0*asin(1.0)];            # Definition of pi
set nEigenI 1;                          # mode i = 1
set nEigenJ 2;                          # mode j = 2
set lambdaN [eigen [expr $nEigenJ]];    # eigenvalue analysis for
nEigenJ modes
set lambdaI [lindex $lambdaN [expr 0]];  # eigenvalue mode i = 1
set lambdaJ [lindex $lambdaN [expr $nEigenJ-1]];# eigenvalue mode j=2
set w1 [expr pow($lambdaI,0.5)];    # w1 (1st mode circular frequency)
set w2 [expr pow($lambdaJ,0.5)];    # w2 (2nd mode circular frequency)
set T1 [expr 2.0*$pi/$w1];          # 1st mode period of the structure
set T2 [expr 2.0*$pi/$w2];          # 2nd mode period of the structure
puts "T1 = $T1 s";                  # display the first mode period in
the command window
puts "T2 = $T2 s";                  # display the second mode period in
the command window

######################################################################
#               Gravity Loads & Gravity Analysis                     #
######################################################################

# apply gravity loads
#command: pattern PatternType $PatternID TimeSeriesType
set w1ext [expr 38.*$KN/$m]; #Distributed Loads of exterior beams on
1st Floor
set wext [expr 36.*$KN/$m]; #Distributed Loads of exterior beams on
other Floors
set wint [expr 4.*$KN/$m]; #Distributed Loads of interior beams on all
Floors
set p1int [expr 134.*$KN];#Axial load on internal piers on 1st Floor
set p1ext [expr 38.*$KN]; #Axial load on external piers on 1st Floor
set pint [expr 130.*$KN]; #Axial load on internal piers on other
Floors
set pext [expr 34.*$KN]; #Axial load on internal piers on other Floors
pattern Plain 101 Constant {
      # Exterior floor distributed loads
      eleLoad -ele 6 9 -type -beamUniform -$w1ext
      eleLoad -ele 15 18 24 27 33 36 42 45 -type -beamUniform -$wext
      # Interior floor distributed loads
      eleLoad -ele 7 8 16 17 25 26 34 35 43 44 -type -beamUniform -
$wint
      # Point loads acting on the frame
```

```
        load 11 0.0 -$p1ext 0.0;
        load 21 0.0 -$p1int 0.0;
        load 31 0.0 -$p1int 0.0;
        load 41 0.0 -$p1int 0.0;
        load 51 0.0 -$p1ext 0.0;
        load 12 0.0 -$pext 0.0;
        load 22 0.0 -$pint 0.0;
        load 32 0.0 -$pint 0.0;
        load 42 0.0 -$pint 0.0;
        load 52 0.0 -$pext 0.0;
        load 13 0.0 -$pext 0.0;
        load 23 0.0 -$pint 0.0;
        load 33 0.0 -$pint 0.0;
        load 43 0.0 -$pint 0.0;
        load 53 0.0 -$pext 0.0;
        load 14 0.0 -$pext 0.0;
        load 24 0.0 -$pint 0.0;
        load 34 0.0 -$pint 0.0;
        load 44 0.0 -$pint 0.0;
        load 54 0.0 -$pext 0.0;
        load 15 0.0 -$pext 0.0;
        load 25 0.0 -$pint 0.0;
        load 35 0.0 -$pint 0.0;
        load 45 0.0 -$pint 0.0;
        load 55 0.0 -$pext 0.0;
}

# Gravity-analysis: load-controlled static analysis
set Tol 1.0e-6;          # convergence tolerance for test
constraints Plain;       # how it handles boundary conditions
numberer RCM;            # renumber dof's to minimize band-width
system BandGeneral;      # how to store and solve the systemofequations
test NormDispIncr $Tol 6;     # determine if convergence has been
achieved at the end of an iteration step
algorithm Newton;              # use Newton's solution algorithm:
updates tangent stiffness at every iteration
set NstepGravity 10;           # apply gravity in 10 steps
set DGravity [expr 1.0/$NstepGravity];    # load increment
integrator LoadControl $DGravity;
analysis Static;
analyze $NstepGravity;
loadConst -time 0.0
puts "Model Built"


######################################################################
#              Recorders                                             #
######################################################################

if {$analysisType == "static"} {
# Record story drifts
recorder Node -file $dataDir/Floor1DispSta.out -node 11 -dof 1 disp;
recorder Node -file $dataDir/Floor2DispSta.out -node 12 -dof 1 disp;
recorder Node -file $dataDir/Floor3DispSta.out -node 23 -dof 1 disp;
recorder Node -file $dataDir/Floor4DispSta.out -node 14 -dof 1 disp;
recorder Node -file $dataDir/Floor5DispSta.out -node 15 -dof 1 disp;
}
```

```
if {$analysisType == "cyclic"} {
	# record top diplacement
	recorder Node -file $dataDir/JointDispCyc.out -time -node 3 -dof
1 disp;
	# record applied force
	recorder Element -file  $dataDir/AppliedForceCyc.out -ele 2
globalForce;
}
if {$analysisType == "pushover"} {
	# record spring rotations
	recorder Element -file $dataDir/AllNodes-Rot-Hist.out -region 7
deformation;
	# record base shear reactions
	recorder Node -file $dataDir/Vbase.out -region 1 -dof 1
reaction;
	# record roof displacement
	recorder Node -file $dataDir/RoofDisp.out -node 15 -dof 1 disp;
}
if {$analysisType == "dynamic"} {
	# record maximum interstory drift
	recorder EnvelopeDrift -file $dataDir/$Outdir -time -iNode 11 12
13 14 15 15 -jNode 10 11 12 13 14 10 -dof 1 -perpDirn 2;
}

######################################################################
#                                                                    #
#                          Analysis Section                          #
#                                                                    #
######################################################################

######################################################################
#                          Static Analysis                           #
######################################################################

if {$analysisType == "static"} {
	puts "Running static analysis..."
	timeSeries Linear 2
# assign lateral loads and create load pattern:  use triangular
distribution
	set lat1 [expr 51.*$KN];	# Lateral force in Floor 1
	set lat2 [expr 87.*$KN];	# Lateral force in Floor 2
	set lat3 [expr 125.*$KN];	# Lateral force in Floor 3
	set lat4 [expr 162.*$KN];	# Lateral force in Floor 4
	set lat5 [expr 224.*$KN];	# Lateral force in Floor 5
	pattern Plain 2 2 {
		load 11 $lat1 0.0 0.0;
		load 12 $lat2 0.0 0.0;
		load 13 $lat4 0.0 0.0;
		load 14 $lat4 0.0 0.0;
		load 15 $lat5 0.0 0.0;
	}
	integrator LoadControl 0.1
	analysis Static
	analyze 10
	puts "Analysis Completed !"
}
```

```
######################################################################
#                       Pushover Analysis                            #
######################################################################

if {$analysisType == "pushover"} {
	puts "Running Pushover..."
# assign lateral loads and create load pattern:  use triangular
distribution
	set lat1 [expr 5.1*$KN];      # Lateral force in Floor 1
	set lat2 [expr 8.7*$KN];      # Lateral force in Floor 2
	set lat3 [expr 12.5*$KN];     # Lateral force in Floor 3
	set lat4 [expr 16.2*$KN];     # Lateral force in Floor 4
	set lat5 [expr 22.4*$KN];     # Lateral force in Floor 5
	pattern Plain 200 Linear {
		load 11 $lat1 0.0 0.0;
		load 12 $lat2 0.0 0.0;
		load 13 $lat4 0.0 0.0;
		load 14 $lat4 0.0 0.0;
		load 15 $lat5 0.0 0.0;
	}

# display deformed shape:
	set ViewScale 2;
	DisplayModel2D DeformedShape $ViewScale ;

# displacement parameters
	set IDctrlNode 11
	set IDctrlDOF 1;
	set Dmax [expr 0.1*$HStory1];
	set Dincr [expr 0.1*$mm];

# analysis commands
	constraints Plain;
	numberer RCM;
	system BandGeneral;
	test NormUnbalance 1.0e-6 800;
	algorithm Newton;
	integrator DisplacementControl  $IDctrlNode   $IDctrlDOF $Dincr;

# use displacement-controlled analysis
	analysis Static;
	set Nsteps [expr int($Dmax/$Dincr
	set ok [analyze $Nsteps];
	puts "Pushover complete";
}

######################################################################
#                              Cyclic Analysis                       #
######################################################################

if {$analysisType == "cyclic"} {
	puts "Running Cyclic Analysis..."
	set lat2 1;
	pattern Plain 200 Linear {
		load 3 -$lat2 0.0 0.0;
```

```
	}


	# we need to set up parameters that are particular to the model.
	set IDctrlNode 3;
	set IDctrlDOF 1;
	# characteristics of pushover analysis
	set iDmax "0.5  0.75 1.0 1.5 2.0 3.0 4.0";
	set Dincr [expr 0.01*$Dy];
	set Fact $Dy;
	set CycleType Full;
	set Ncycles 3;

# ----------- set up analysis parameters
	source LibAnalysisStaticParameters.tcl;	#
#  ---------- perform Static Cyclic Displacements Analysis
	source GeneratePeaks.tcl
	set fmt1 "%s Cyclic analysis: CtrlNode %.1i, dof %.1i, Disp=%.3f
%s";	# format for screen/file output of DONE/PROBLEM analysis
	foreach Dmax $iDmax {
		set iDstep [GeneratePeaks $Dmax $Dincr $CycleType $Fact];
	# this proc is defined above
		for {set i 1} {$i <= $Ncycles} {incr i 1} {
			set zeroD 0
			set D0 0.0
			foreach Dstep $iDstep {
				set D1 $Dstep
				set Dincr [expr $D1 - $D0]
				integrator DisplacementControl  $IDctrlNode
$IDctrlDOF $Dincr
				analysis Static
				# -------------first analyze command-----------
				set ok [analyze 1]
				# -----------if convergence failure------------
				if {$ok != 0} {
				# if analysis fails, we try some other stuff
					if {$ok != 0} {
						puts "Trying Newton with Initial
Tangent .."
						test NormDispIncr   $Tol 2000 0
						algorithm Newton -initial
						set ok [analyze 1]
						test $testTypeStatic $TolStatic
$maxNumIterStatic    0
						algorithm $algorithmTypeStatic
					}
					if {$ok != 0} {
						puts "Trying Broyden .."
						algorithm Broyden 8
						set ok [analyze 1 ]
						algorithm $algorithmTypeStatic
					}
					if {$ok != 0} {
						puts "Trying NewtonWithLineSearch"
						algorithm NewtonLineSearch 0.8
						set ok [analyze 1]
						algorithm $algorithmTypeStatic
					}
```

```
                                        if {$ok != 0} {
                                                set putout [format $fmt1 "PROBLEM" 
$IDctrlNode $IDctrlDOF [nodeDisp $IDctrlNode $IDctrlDOF] $LunitTXT]
                                                puts $putout
                                                return -1
                                        }; # end if
                                }; # end if
                                # -------------------------------------------
                                set D0 $D1; # move to next step
                        }; # end Dstep
                };      # end i
        };      # end of iDmaxCycl
        # ------------------------------------------------------------------
        if {$ok != 0 } {
                puts [format $fmt1 "PROBLEM" $IDctrlNode $IDctrlDOF 
[nodeDisp $IDctrlNode $IDctrlDOF] $LunitTXT]
        } else {
                puts "CYCLIC ANALYSIS COMPLETED."
        }
}

######################################################################
#                       Time History/Dynamic Analysis                #
######################################################################

if {$analysisType == "dynamic"} {
        puts "Running dynamic analysis..."
        # display deformed shape:
        set ViewScale 2;  # amplify display of deformed shape
        DisplayModel2D DeformedShape $ViewScale;

        # Uniform Earthquake ground motion
        set GMdirection 1;              # ground-motion direction
        set GMrecord "$GMdir/$GMname.gm";# ground-motion file names
        set GMfact $GMscale;            # ground-motion scaling factor

        # set up ground-motion-analysis parameters
        set DtAnalysis [expr 0.1*$sec]; # time-step Dt
        set TmaxAnalysis [expr 1.0*$maxtime*$sec];
        set dt [expr 1.0*$dtime*$sec];  # timestep of input GM file

        # ----------- set up analysis parameters
        source LibAnalysisDynamicParameters.tcl;  #

        # define DAMPING-----------------------------------------------
        set xDamp 0.05;                 # 5% damping ratio
        set lambda [eigen 1];           # eigenvalue mode 1
        set omega [expr pow($lambda,0.5)];
        set alphaM 0.;                  # M-prop. damping; D = alphaM*M
        set betaKcurr 0.;               # K-proportional damping;
        set betaKcomm [expr 2.*$xDamp/($omega)]; # K-prop. damping
        set betaKinit 0.;       # initial-stiffness proportional damping
        rayleigh $alphaM $betaKcurr $betaKinit $betaKcomm;

        #  ------- perform Dynamic Ground-Motion Analysis
        set IDloadTag 400;      # for uniformSupport excitation
        # Uniform EXCITATION: acceleration input
        set GMfatt [expr $cm*$GMfact/$sec/$sec];
```

```
	set AccelSeries "Series -dt $dt -filePath $GMrecord -factor
$GMfatt";	# time series information
	pattern UniformExcitation  $IDloadTag  $GMdirection -accel
$AccelSeries  ;		# create Uniform excitation
	set Nsteps [expr int($TmaxAnalysis/$DtAnalysis)];
	set ok [analyze $Nsteps $DtAnalysis];
	if {$ok != 0} {      ;
	# ----------------------------------------------------------------
		# change some analysis parameters to achieve convergence
		# performance is slower inside this loop
		# Time-controlled analysis
		set ok 0;
		set controlTime [getTime];
		while {$controlTime < $TmaxAnalysis && $ok == 0} {
			set controlTime [getTime]
			set ok [analyze 1 $DtAnalysis]
			if {$ok != 0} {
				puts "Trying Newton with Initial Tangent .."
				test NormDispIncr   $Tol 1000  0
				algorithm Newton -initial
				set ok [analyze 1 $DtAnalysis]
				test $testTypeDynamic $TolDynamic
$maxNumIterDynamic  0
				algorithm $algorithmTypeDynamic
			}
			if {$ok != 0} {
				puts "Trying Broyden .."
				algorithm Broyden 8
				set ok [analyze 1 $DtAnalysis]
				algorithm $algorithmTypeDynamic
			}
			if {$ok != 0} {
				puts "Trying NewtonWithLineSearch .."
				algorithm NewtonLineSearch .8
				set ok [analyze 1 $DtAnalysis]
				algorithm $algorithmTypeDynamic
			}
		}
	};	# end if ok !0
	puts "Ground Motion Done. End Time: [getTime]"
}
wipe all;
```

```
#Run all groundmotion data in THA analysis
set dataDir Data(allmodels);     # set up name of data directory
file mkdir $dataDir;             # create data directory
set GMdir "GMRecords";            # ground-motion file directory
set EQList [open "EQList.txt" r];
set GMname {};
set GMscale {};
set drift1 {};
set drift2 {};
set drift3 {};
set drift4 {};
set drift5 {};
set drift6 {};
foreach line [split [read $EQList] \n] {
      set GMname [lindex $line 0]
      set GMscale [lindex $line 1]
      set GMfile [open $GMdir/$GMname.THF r]
      set var1 {};
      set var2 {};
      set var3 {};
      foreach line [split [read $GMfile] \n] {
            lappend var1  [lindex $line 0]
            lappend var2 [lindex $line 1]
            lappend var3 [lindex $line 2]
      }
      set accel [lrange $var2 0 end-1]
      set dtime [expr [lindex $var1 1]-[lindex $var1 0]]
      set maxtime [lindex $var1 end-1]
      set gmout [open "$GMdir/$GMname.gm" w]
      puts $gmout $accel
      close $gmout
      set Outdir "$GMname.out"
      source Real2DWide.tcl
      #collect all drift data into a file
      set frag [open $dataDir/$Outdir r]
      set driftvar1 {};
      set driftvar2 {};
      set driftvar3 {};
      set driftvar4 {};
      set driftvar5 {};
      set driftvar6 {};
      foreach line [split [read $frag] \n] {
            lappend driftvar1 [lindex $line 1]
            lappend driftvar2 [lindex $line 3]
            lappend driftvar3 [lindex $line 5]
            lappend driftvar4 [lindex $line 7]
            lappend driftvar5 [lindex $line 9]
            lappend driftvar6 [lindex $line 11]
      }
      lappend drift1 [lindex $driftvar1 end-1];
      lappend drift2 [lindex $driftvar2 end-1];
      lappend drift3 [lindex $driftvar3 end-1];
      lappend drift4 [lindex $driftvar4 end-1];
      lappend drift5 [lindex $driftvar5 end-1];
      lappend drift6 [lindex $driftvar6 end-1];
}
```

```
#write the data into a file
set driftout [open "DriftOut1.txt" w]
puts $driftout $drift1
close $driftout
set driftout [open "DriftOut2.txt" w]
puts $driftout $drift2
close $driftout
set driftout [open "DriftOut3.txt" w]
puts $driftout $drift3
close $driftout
set driftout [open "DriftOut4.txt" w]
puts $driftout $drift4
close $driftout
set driftout [open "DriftOut5.txt" w]
puts $driftout $drift5
close $driftout
set driftout [open "DriftOut6.txt" w]
puts $driftout $drift6

close $driftout
```

B.4. OpenSees Code Files Required for All Models

```
# Calibration Data for Ibarra-Krawinkler Hysteresis Calibration
# ENES KARAASLAN

######################################################################
#      Peak Oriented Ibarra-Krawinkler Deterioration Material        #
######################################################################

proc IbarraMatConvFrame {mat Ke Mypos Myneg tetp tetpc McMy} {
      source units.tcl
      set matTag_Col $mat;    # Material tag for wide beam spring
      set Ko [expr 1.5*$Ke*$KN*$m];                 # Initial Stiffness
      set My_pos [expr 1.15*$Mypos*$KN*$m];     # Positive yield moment
      set My_neg [expr 1.15*$Myneg*$KN*$m];     # Negative yield moment
      set L_S 1.0;      # basic strength deterioration
      set L_K 1.0;      # unloading stiffness deterioration
      set L_A 1.0;      # accelerated reloading stiffness deterioration
      set L_C 1.0;      # post-capping strength deterioration
      set c_S 1.0;      # exponent for basic strength deterioration
      set c_K 1.0;      # exponent forunloading stiffness deterioration
      set c_A 1.0;      # accelerated reloading stiffness deterioration
      set c_C 1.0;      # post-capping strength deterioration exponent
      set th_pP [expr 1.0*$tetp];  # plastic rot capacity +
      set th_pN [expr 1.0*$tetp];  # plastic rot capacity -
      set th_pcP [expr 1.0*$tetpc]; # post-capping rot capacity +
      set th_pcN [expr 1.0*$tetpc]; # post-capping rot capacity -
      set Res_pos 0.20;            # residual strength ratio +
      set Res_neg 0.20;            # residual strength ratio -
      set th_uP 0.4;               # ultimate rot capacity +
      set th_uN 0.4;               # ultimate rot capacity -
      set D_pos 1.0;               # rate of cyclic deterioration +
      set D_neg 1.0;               # rate of cyclic deterioration -
      set Mc_My $McMy;             # Post yield strength ratio
      set as_pos [expr $Mc_My/$th_pP/$Ke];# + strain hardening ratio
      set as_neg [expr $Mc_My/$th_pN/$Ke];# - strain hardening ratio

      uniaxialMaterial ModIMKPeakOriented $matTag_Col $Ko $as_pos
$as_neg $My_pos $My_neg $L_S $L_C $L_A $L_K $c_S $c_C $c_A $c_K $th_pP
$th_pN $th_pcP $th_pcN $Res_pos $Res_neg $th_uP $th_uN $D_pos $D_neg
      WrVar $matTag_Col [expr 1.0*$My_pos/$Ko] [expr
1.0*$My_pos/$Ko+$th_pP] [expr 1.0*$My_pos/$Ko+$th_pP+$th_pcP]
"CritRots.out"
}

proc IbarraMatNew {mat Ke Mypos Myneg tetp tetpc McMy} {
      source units.tcl
      set matTag_Col $mat;    # Material tag for wide beam spring
      set Ko [expr 1.5*$Ke*$KN*$m];        # Initial Stiffness
      set My_pos [expr 0.85*$Mypos*$KN*$m];     # Positive yield moment
      set My_neg [expr 0.85*$Myneg*$KN*$m];     # Negative yield moment
      set L_S 1.0;      # basic strength deterioration
      set L_K 1.0;      # unloading stiffness deterioration
      set L_A 1.0;      # accelerated reloading stiffness deterioration
      set L_C 1.35; # post-capping strength deterioration
      set c_S 0.85; # exponent for basic strength deterioration
      set c_K 1.0;  # exponent for unloading stiffness deterioration
```

```
	set c_A 1.0;  # exponent for reloading stiffness deterioration
	set c_C 1.0;  # exponent for post-capping strength deterioration
	set th_pP [expr 1.0*$tetp];   # plastic rot capacity +
	set th_pN [expr 1.0*$tetp];   # plastic rot capacity -
	set th_pcP [expr 1.0*$tetpc]; # post-capping rot capacity +
	set th_pcN [expr 1.0*$tetpc]; # post-capping rot capacity -
	set Res_pos 0.20;             # residual strength ratio +
	set Res_neg 0.20;             # residual strength ratio -
	set th_uP 0.4;                # ultimate rot capacity +
	set th_uN 0.4;                # ultimate rot capacity -
	set D_pos 1.0;                # rate of cyclic deterioration +
	set D_neg 1.0;                # rate of cyclic deterioration -
	set Mc_My $McMy;              # Post yield strength ratio
	set as_pos [expr $Mc_My/$th_pP/$Ke];# + strain hardening ratio
	set as_neg [expr $Mc_My/$th_pN/$Ke];# - strain hardening ratio
	uniaxialMaterial ModIMKPeakOriented $matTag_Col $Ko $as_pos
$as_neg $My_pos $My_neg $L_S $L_C $L_A $L_K $c_S $c_C $c_A $c_K $th_pP
$th_pN $th_pcP $th_pcN $Res_pos $Res_neg $th_uP $th_uN $D_pos $D_neg
	WrVar $matTag_Col [expr 1.0*$My_pos/$Ko] [expr
1.0*$My_pos/$Ko+$th_pP] [expr 1.0*$My_pos/$Ko+$th_pP+$th_pcP]
"CritRots.out"
}

######################################################################
#                    Yield Strength Prediction                       #
######################################################################

proc YieldStrPos {b deff rc rt rs ky phi dr Ec Es} {
	return [expr
0.5*$phi*$b*pow($deff,3)*($Ec*pow($ky,2)/2*(0.5*(1+$dr)-
$ky/3)+0.5*$Es*(1-$dr)*((1-$ky)*$rc+($ky-$dr)*$rt+(1-
$dr)*$rs/6))/pow(1000,2)]
}
proc YieldStrNeg {b deff rc rt rs ky phi dr Ec Es} {
	return [expr -
0.5*$phi*$b*pow($deff,3)*($Ec*pow($ky,2)/2*(0.5*(1+$dr)-
$ky/3)+0.5*$Es*(1-$dr)*((1-$ky)*$rc+($ky-$dr)*$rt+(1-
$dr)*$rs/6))/pow(1000,2)]
}

######################################################################
#                   Initial Stifness Prediction                      #
######################################################################

proc IntStiff {P Ag fc Ec b d} {
	set stiff [expr 0.17+1.61*$P/$Ag/$fc/1000.]
	set gross [expr $Ec*$b*pow($d,3)/12/pow(1000,3)]
	if {$stiff < 0.35} {
		return [expr 0.35*$gross]
	} elseif {$stiff > 0.8} {
		return [expr 0.8*$gross]
	} else {
		return [expr $stiff*$gross]
	}
}
```

```
######################################################################
#                  Yield Rotation Prediction                         #
######################################################################

proc PostYieldRot {fc v asl rs} {
      return [expr
0.13*(1.+0.55*$asl)*pow(0.13,$v)*pow((0.02+40.*$rs),0.65)*pow(0.57,(0.
01*$fc))]
}

######################################################################
#                  Post-Capping Rotation Prediction                  #
######################################################################

proc PostCapRot {fc v asl rs} {
      set caprot [expr 0.76*pow(0.031,$v)*pow((0.02+40.*$rs),1.02)]
      if {$caprot > 0.1} {
            return 0.1
      } else {
            return $caprot
      }
}

######################################################################
#                  Mc/My Prediction                                  #
######################################################################

proc McMy {fc v} {
      return [expr 1.25*pow(0.89,$v)*pow(0.91,(0.01*$fc))]
}

######################################################################
#                  Calibration Function Definition                   #
######################################################################

proc Calibration {mtag Econc Esteel width depth cover fconc fsteel
axial compr tens shear barslip} {
      #Geometry and Material Input Para.
      set b $width;                  #Member Width
      set d $depth;                  #Member Depth
      set dc $cover;                 #Cover Depth
      set fc $fconc;                 #Concrete Strength
      set fy $fsteel;                #Steel Yield Strength
      set P $axial;                  #Member Axial Load
      set rs $shear;                 #Reinforcement Ratio Shear
      set rc $compr;                 #Reinforcement Ratio Compressive
      set rt $tens;                  #Reinforcement Ratio Tensile
      set asl $barslip;              #Bar Slip Parameter either 0 or 1
      set mat $mtag;                 #define material tag
      set Ec $Econc;
      set Es $Esteel;
```

```
	#Geometry and Material Calculated Para.
	set deff [expr $d-$cover];          #Effective Depth
	set Ag [expr $b*$d/pow(1000.,2)];   #Member Gross Area
	set v [expr $P/$Ag/$fc/1000.];      #Axial Load Ratio
	set n [expr 1.0*$Es/$Ec];           #Ey/Ec
	set dr [expr 1.0*$dc/$deff];        #Cover/Effective Depth Ratio
	set A [expr $rc+$rt+$rs+$P*1000./$b/$deff/$fy];
	set B [expr $rc+$rt*$dr+$rs*0.5*(1.0+$dr)+$P*1000./$b/$deff/$fy]
	set ky [expr sqrt(pow($n,2)*pow($A,2)+2*$n*$B)-$n*$A];
	set phi [expr 1.8*$fc/$Ec/$ky/$deff];
	IbarraMatNew $mat [IntStiff $P $Ag $fc $Ec $b $d] [YieldStrPos
$b $deff $rc $rt $rs $ky $phi $dr $Ec $Es] [YieldStrNeg $b $deff $rt
$rc $rs $ky $phi $dr $Ec $Es] [PostYieldRot $fc $v $asl $rs]
[PostCapRot $fc $v $asl $rs] [McMy $fc $v]
}
proc CalibrationConvFrame {mtag Econc Esteel width depth cover fconc
fsteel axial compr tens shear barslip} {
	#Geometry and Material Input Para.
	set b $width;                 #Member Width
	set d $depth;                 #Member Depth
	set dc $cover;                #Cover Depth
	set fc $fconc;                #Concrete Strength
	set fy $fsteel;               #Steel Yield Strength
	set P $axial;                 #Member Axial Load
	set rs $shear;                #Reinforcement Ratio Shear
	set rc $compr;                #Reinforcement Ratio Compressive
	set rt $tens;                 #Reinforcement Ratio Tensile
	set asl $barslip;             #Bar Slip Parameter either 0 or 1
	set mat $mtag;                #define material tag
	set Ec $Econc;
	set Es $Esteel;
	#Geometry and Material Calculated Para.
	set deff [expr $d-$cover];          #Effective Depth
	set Ag [expr $b*$d/pow(1000.,2)];   #Member Gross Area
	set v [expr $P/$Ag/$fc/1000.];      #Axial Load Ratio
	set n [expr 1.0*$Es/$Ec];           #Ey/Ec
	set dr [expr 1.0*$dc/$deff];        #Cover/Effective Depth Ratio
	set A [expr $rc+$rt+$rs+$P*1000./$b/$deff/$fy];
	set B [expr $rc+$rt*$dr+$rs*0.5*(1.0+$dr)+$P*1000./$b/$deff/$fy]
	set ky [expr sqrt(pow($n,2)*pow($A,2)+2*$n*$B)-$n*$A];
	set phi [expr 1.8*$fc/$Ec/$ky/$deff];
	IbarraMatConvFrame $mat [IntStiff $P $Ag $fc $Ec $b $d]
[YieldStrPos $b $deff $rc $rt $rs $ky $phi $dr $Ec $Es] [YieldStrNeg
$b $deff $rt $rc $rs $ky $phi $dr $Ec $Es] [PostYieldRot $fc $v $asl
$rs] [PostCapRot $fc $v $asl $rs] [McMy $fc $v]
}
# Write variables to text
proc WrVar {var1 var2 var3 var4 name} {
	set variable [open $name "w"]
	puts "material: $var1"
	puts "YieldRot: $var2"
	puts "CapRot: $var3"
	puts "FailRot: $var4"
	close $variable

}
```

```
# ------------------------------------------
# LibUnits.tcl -- define system of units
# Enes Karaaslan METU
# define UNITS ----------------------------
set in 1.;                    # define basic units -- output units
set kip 1.;                   # define basic units -- output units
set sec 1.;                   # define basic units -- output units
set LunitTXT "inch";          # define basic-unit text for output
set FunitTXT "kip";           # define basic-unit text for output
set TunitTXT "sec";           # define basic-unit text for output
set ft [expr 12.*$in];        # define engineering units
set ksi [expr $kip/pow($in,2)];
set psi [expr $ksi/1000.];
set lbf [expr $psi*$in*$in];        # pounds force
set pcf [expr $lbf/pow($ft,3)];     # pounds per cubic foot
set psf [expr $lbf/pow($ft,2)];     # pounds per square foot
set in2 [expr $in*$in];             # inch^2
set in4 [expr $in*$in*$in*$in];     # inch^4
set cm [expr $in/2.54];             # centimetre
set PI [expr 2*asin(1.0)];          # define constants
set g [expr 32.2*$ft/pow($sec,2)];  # gravitational acceleration
set Ubig 1.e10;                     # a really large number
set Usmall [expr 1/$Ubig];          # a really small number
set MPa [expr 145.04*$psi];         # MegaPascal
set meter [expr 100.*$cm];          # metric unit
set mm [expr 0.1*$cm]
set m [expr 100.*$cm]
set mm2 [expr $mm*$mm]
set N [expr 0.00022481*$kip]
set KN [expr 1000.*$N]
```

```
######################################################################
## display Node Numbers, Deformed or Mode Shape in 2D problem       ##
##                Silvia Mazzoni & Frank McKenna, 2006              ##
######################################################################

# DisplayModel2D$ShapeType $dAmp $xLoc $yLoc $xPixels $yPixels $nEigen

proc DisplayModel2D { {ShapeType nill} {dAmp 5}  {xLoc 10} {yLoc 10}
{xPixels 512} {yPixels 384} {nEigen 1} } {
      global TunitTXT;                # load time-unit text
      global ScreenResolutionX ScreenResolutionY; # read global values
for screen resolution
      if {  [info exists TunitTXT] != 1} {set TunitTXT ""}; # set
blank if it has not been defined previously.
      if {  [info exists ScreenResolutionX] != 1} {set
ScreenResolutionX 1024};# set default if it has not been defined
previously.
      if {  [info exists ScreenResolutionY] != 1} {set
ScreenResolutionY 768}; # set default if it has not been defined
previously.
      if {$xPixels == 0} {
            set xPixels [expr int($ScreenResolutionX/2)];
            set yPixels [expr int($ScreenResolutionY/2)]
            set xLoc 10
            set yLoc 10
      }
      if {$ShapeType == "nill"} {
            puts ""; puts ""; puts "------------------"
            puts "View the Model? (N)odes, (D)eformedShape,
anyMode(1),(2),(#). Press enter for NO."
            gets stdin answer
            if {[llength $answer]>0 } {
                  if {$answer != "N" & $answer != "n"} {
                        puts "Modify View Scaling Factor=$dAmp? Type
factor, or press enter for NO."
                        gets stdin answerdAmp
                        if {[llength $answerdAmp]>0 } {
                              set dAmp $answerdAmp
                        }
                  }
                  if {[string index $answer 0] == "N" || [string index
$answer 0] == "n"} {
                        set ShapeType NodeNumbers
                  } elseif {[string index $answer 0] == "D" ||[string
index $answer 0] == "d" } {
                        set ShapeType DeformedShape
                  } else {
                        set ShapeType ModeShape
                        set nEigen $answer
                  }
            } else {
                  return
            }
      }
      if {$ShapeType ==  "ModeShape" } {
            set lambdaN [eigen $nEigen];        # perform eigenvalue
analysis for ModeShape
            set lambda [lindex $lambdaN [expr $nEigen-1]];
```

```
            set omega [expr pow($lambda,0.5)]
            set PI      [expr 2*asin(1.0)];           # define constant
            set Tperiod [expr 2*$PI/$omega];          # period (sec.)
            set fmt1 "Mode Shape, Mode=%.1i Period=%.3f %s  "
            set windowTitle [format $fmt1 $nEigen $Tperiod  $TunitTXT]
      } elseif  {$ShapeType ==  "NodeNumbers" } {
            set windowTitle "Node Numbers"
      } elseif  {$ShapeType ==  "DeformedShape" } {
            set windowTitle "Deformed Shape"
      }

      set viewPlane XY
      recorder display $windowTitle $xLoc $yLoc $xPixels $yPixels  -
wipe ; # display recorder
      DisplayPlane $ShapeType $dAmp $viewPlane $nEigen 0
      after 2000; #pause for 2 seconds to display
}
```

```
######################################################################
## setup display parameters for specified viewPlane and display    ##
##                Silvia Mazzoni & Frank McKenna, 2006              ##
######################################################################

# DisplayPlane $ShapeType $dAmp $viewPlane $nEigen $quadrant
proc DisplayPlane {ShapeType dAmp viewPlane {nEigen 0}  {quadrant 0}}
{
	set Xmin [lindex [nodeBounds] 0];	# view bounds in global
coords - will add padding on the sides
	set Ymin [lindex [nodeBounds] 1];
	set Zmin [lindex [nodeBounds] 2];
	set Xmax [lindex [nodeBounds] 3];
	set Ymax [lindex [nodeBounds] 4];
	set Zmax [lindex [nodeBounds] 5];
	set Xo 0;	# center of local viewing system
	set Yo 0;
	set Zo 0;
	set uLocal [string index $viewPlane 0];	# viewPlane local-x
axis in global coordinates
	set vLocal [string index $viewPlane 1];	# viewPlane local-y
axis in global coordinates
	if  {$viewPlane =="3D" } {
		set uMin $Zmin+$Xmin
		set uMax $Zmax+$Xmax
		set vMin $Ymin
		set vMax $Ymax
		set wMin -10000
		set wMax 10000
		vup 0 1 0; # dirn defining up direction of view plane
	} else {
		set keyAxisMin "X $Xmin Y $Ymin Z $Zmin"
		set keyAxisMax "X $Xmax Y $Ymax Z $Zmax"
		set axisU [string index $viewPlane 0];
		set axisV [string index $viewPlane 1];
		set uMin [string map $keyAxisMin $axisU]
		set uMax [string map $keyAxisMax $axisU]
		set vMin [string map $keyAxisMin $axisV]
		set vMax [string map $keyAxisMax $axisV]
		if {$viewPlane =="YZ" || $viewPlane =="ZY" } {
			set wMin $Xmin
			set wMax $Xmax
		} elseif  {$viewPlane =="XY" || $viewPlane =="YX" } {
			set wMin $Zmin
			set wMax $Zmax
		} elseif  {$viewPlane =="XZ" || $viewPlane =="ZX" } {
			set wMin $Ymin
			set wMax $Ymax
		} else {
		return -1
		}
	}
	set epsilon 1e-3; # make windows width or height not zero when
the Max and Min values of a coordinate are the same
	set uWide [expr $uMax - $uMin+$epsilon];
	set vWide [expr $vMax - $vMin+$epsilon];
	set uSide [expr 0.25*$uWide];
	set vSide [expr 0.25*$vWide];
```

```
      set uMin [expr $uMin - $uSide];
      set uMax [expr $uMax + $uSide];
      set vMin [expr $vMin - $vSide];
      set vMax [expr $vMax + 2*$vSide];   # pad a little more on top,
because of window title
      set uWide [expr $uMax - $uMin+$epsilon];
      set vWide [expr $vMax - $vMin+$epsilon];
      set uMid [expr ($uMin+$uMax)/2];
      set vMid [expr ($vMin+$vMax)/2];
      # keep the following general, as change the X and Y and Z for
each view plane
      # next three commmands define viewing system, all values in
global coords
      vrp $Xo $Yo $Zo;     # point on the view plane in global coord,
center of local viewing system
      if {$vLocal == "X"} {
            vup 1 0 0; # dirn defining up direction of view plane
      } elseif {$vLocal == "Y"} {
            vup 0 1 0; # dirn defining up direction of view plane
      } elseif {$vLocal == "Z"} {
            vup 0 0 1; # dirn defining up direction of view plane
      }
      if {$viewPlane =="YZ" } {
            vpn 1 0 0; # direction of outward normal to view plane
            prp 10000. $uMid $vMid ; # eye location in local coord sys
defined by viewing system
            plane 10000 -10000; # distance to front and back clipping
planes from eye
      } elseif  {$viewPlane =="ZY" } {
            vpn -1 0 0; # direction of outward normal to view plane
            prp -10000. $vMid $uMid ; # eye location in local coord sys
defined by viewing system
            plane 10000 -10000; # distance to front and back clipping
planes from eye
      } elseif  {$viewPlane =="XY"  } {
            vpn 0 0 1; # direction of outward normal to view plane
            prp $uMid $vMid 10000; # eye location in local coord sys
defined by viewing system
            plane 10000 -10000; # distance to front and back clipping
planes from eye
      } elseif  {$viewPlane =="YX" } {
            vpn 0 0 -1; # direction of outward normal to view plane
            prp $uMid $vMid -10000; # eye location in local coord sys
defined by viewing system
            plane 10000 -10000; # distance to front and back clipping
planes from eye
      } elseif  {$viewPlane =="XZ" } {
            vpn 0 -1 0; # direction of outward normal to view plane
            prp $uMid -10000 $vMid ; # eye location in local coord sys
defined by viewing system
            plane 10000 -10000; # distance to front and back clipping
planes from eye
      } elseif  {$viewPlane =="ZX" } {
            vpn 0 1 0; # direction of outward normal to view plane
            prp $uMid 10000 $vMid ; # eye location in local coord sys
defined by viewing system
            plane 10000 -10000; # distance to front and back clipping
planes from eye
```

```
	} elseif  {$viewPlane =="3D" } {
		vpn 1 0.25 1.25; # direction of outward normal to view
plane
		prp -100 $vMid 10000; # eye location in local coord sys
defined by viewing system
		plane 10000 -10000; # distance to front and back clipping
planes from eye
	}  else {
		return -1
	}
	# next three commands define view, all values in local coord
system
	if  {$viewPlane =="3D" } {
		viewWindow [expr $uMin-$uWide/4] [expr $uMax/2] [expr
$vMin-0.25*$vWide] [expr $vMax]
	} else {
		viewWindow $uMin $uMax $vMin $vMax
	}
	projection 1;	# projection mode, 0:prespective, 1: parallel
	fill 1;		# fill mode; needed only for solid elements

	if {$quadrant == 0} {
		port -1 1 -1 1	# area of window that will be drawn into
(uMin,uMax,vMin,vMax);
	} elseif {$quadrant == 1} {
		port 0 1 0 1	# area of window that will be drawn into
(uMin,uMax,vMin,vMax);
	} elseif {$quadrant == 2} {
		port -1 0 0 1	# area of window that will be drawn into
(uMin,uMax,vMin,vMax);
	} elseif {$quadrant == 3} {
		port -1 0 -1 0	# area of window that will be drawn into
(uMin,uMax,vMin,vMax);
	} elseif {$quadrant == 4} {
		port 0 1 -1 0	# area of window that will be drawn into
(uMin,uMax,vMin,vMax);
	}

	if {$ShapeType ==  "ModeShape" } {
		display -$nEigen 0  [expr 5.*$dAmp];	# display mode
shape for mode $nEigen
	} elseif  {$ShapeType ==  "NodeNumbers" } {
		display 1 -1 0  ;		# display node numbers
	} elseif  {$ShapeType ==  "DeformedShape" }  {
		display 1 2 $dAmp;		# display deformed shape  the
2 makes the nodes small
	}
};




# ------------------------------------------------------------------
# dynamic-analysis parameters
```

```
# Set up Analysis Parameters -----------------------------------------
# CONSTRAINTS handler -- Determines how the constraint equations are
enforced in the analysis
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/617.htm)
variable constraintsTypeDynamic Transformation;
constraints $constraintsTypeDynamic ;
# DOF NUMBERER (number the degrees of freedom in the domain):
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/366.htm)
variable numbererTypeDynamic RCM
numberer $numbererTypeDynamic
# SYSTEM
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/371.htm)
variable systemTypeDynamic BandGeneral;   # try UmfPack for large
problems
system $systemTypeDynamic

# TEST: # convergence test to
# Convergence TEST
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/360.htm)
variable TolDynamic 1.e-8;       # Convergence Test: tolerance
variable maxNumIterDynamic 10;
variable printFlagDynamic 0;
variable testTypeDynamic EnergyIncr;      # Convergence-test type
test $testTypeDynamic $TolDynamic $maxNumIterDynamic
$printFlagDynamic;
# for improved-convergence procedure:
variable maxNumIterConvergeDynamic 2000;
variable printFlagConvergeDynamic 0;
# Solution ALGORITHM: - Iterate from the last time step to the current
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/682.htm)
variable algorithmTypeDynamic ModifiedNewton
algorithm $algorithmTypeDynamic;
# Static INTEGRATOR: -- determine the next time step for an analysis
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/689.htm)
variable NewmarkGamma 0.5;    # Newmark-integrator gamma parameter
(also HHT)
variable NewmarkBeta 0.25;    # Newmark-integrator beta parameter
variable integratorTypeDynamic Newmark;
integrator $integratorTypeDynamic $NewmarkGamma $NewmarkBeta
# ANALYSIS  -- defines what type of analysis is to be performed
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/324.htm)
variable analysisTypeDynamic Transient
analysis $analysisTypeDynamic
```

```
# ---------------------------------------------------------------------
# static analysis parameters
# I am setting all these variables as global variables
# so that these variables can be uploaded by a procedure
# Silvia Mazzoni & Frank McKenna, 2006
#
# CONSTRAINTS handler -- Determines how the constraint equations are
enforced in the analysis
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/617.htm)

variable constraintsTypeStatic Plain;          # default;
if {  [info exists RigidDiaphragm] == 1} {
      if {$RigidDiaphragm=="ON"} {
            variable constraintsTypeStatic Lagrange;  #     for large
model, try Transformation
      };    # if rigid diaphragm is on
};    # if rigid diaphragm exists
constraints $constraintsTypeStatic

# DOF NUMBERER (number the degrees of freedom in the domain):
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/366.htm)
set numbererTypeStatic RCM
numberer $numbererTypeStatic

# SYSTEM
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/371.htm)
#   Linear Equation Solvers (how to store and solve the system of
equations in the analysis)
set systemTypeStatic BandGeneral;        # try UmfPack for large model
system $systemTypeStatic

# TEST: # convergence test to
# Convergence TEST
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/360.htm)
variable TolStatic 1.e-8
variable maxNumIterStatic 6;
variable printFlagStatic 0;
variable testTypeStatic EnergyIncr ;
test $testTypeStatic $TolStatic $maxNumIterStatic $printFlagStatic;
# for improved-convergence procedure:
variable maxNumIterConvergeStatic 2000;
variable printFlagConvergeStatic 0;

# Solution ALGORITHM: -- Iterate from the last time step to the
current
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/682.htm)
variable algorithmTypeStatic Newton
algorithm $algorithmTypeStatic;

# Static INTEGRATOR: -- determine the next time step for an analysis
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/689.htm)
integrator DisplacementControl  $IDctrlNode   $IDctrlDOF $Dincr

# ANALYSIS  -- defines what type of analysis is to be performed
(http://opensees.berkeley.edu/OpenSees/manuals/usermanual/324.htm)
set analysisTypeStatic Static
analysis $analysisTypeStatic
```

```
######################################################################
##                  READ PROCEDURE FOR EARTHQAUKE INPUT                 ##
######################################################################

proc ReadSMDFile {inFilename outFilename dt} {
      # The header in the PEER record is, e.g., formatted as follows:
      # PACIFIC ENGINEERING AND ANALYSIS STRONG-MOTION DATA
      # IMPERIAL VALLEY 10/15/79 2319, EL CENTRO ARRAY 6, 230
      # ACCELERATION TIME HISTORY IN UNITS OF G
      #  NPTS=  3930, DT= .00500 SEC
      upvar $dt DT;           # Pass dt by reference
      # Open the input file and catch the error if it can't be read
      if [catch {open $inFilename r} inFileID] {
            puts stderr "Cannot open $inFilename for reading"
      } else {
            # Open output file for writing
            set outFileID [open $outFilename w]
            # Flag indicating dt is found and that ground motion
            # values should be read -- ASSUMES dt is on last line
            # of header!!!
            set flag 0
            # Look at each line in the file
            foreach line [split [read $inFileID] \n] {
                  if {[llength $line] == 0} {
                        # Blank line --> do nothing
                        continue
                  } elseif {$flag == 1} {
                        # Echo ground motion values to output file
                        puts $outFileID $line
                  } else {
                        # Search header lines for dt
                        foreach word [split $line] {
                              # Read in the time step
                              if {$flag == 1} {
                                    set DT $word
                                    break
                              }
                              # Find the desired token and set the flag
                              if {[string match $word "DT="] == 1} {set
      flag 1}
                              }
                        }
                  }
            close $outFileID; # Close the output file
            close $inFileID;  # Close the input file
            }
      }
```