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Evaluation Of Collapse Indicators For Seismically Vulnerable Reinforced Concrete Buildings

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Graduate School Form 30
(Revised 08/14)

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Nicholas R. Skok

Entitled
EVALUATION OF COLLAPSE INDICATORS FOR SEISMICALLY VULNERABLE REINFORCED CONCRETE BUILDINGS

For the degree of Master of Science in Civil Engineering

Is approved by the final examining committee:

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EVALUATION OF COLLAPSE INDICATORS FOR SEISMICALLY VULNERABLE REINFORCED CONCRETE BUILDINGS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Nicholas R. Skok

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Civil Engineering

December 2014

Purdue University

West Lafayette, Indiana

To my parents.

ACKNOWLEDGMENTS

This study would not have been possible without the help from several people. I would like to recognize and thank them for their contributions.

I greatly appreciate the funding I received from Purdue University through the John E. Goldberg Fellowship and the National Science Foundation through Grant 0618804 thanks to Professor Jack Moehle from the University of California at Berkeley.

Thank you Professor Santiago Pujol for your abundant knowledge and support during the past two years on this project. My appreciation of reinforced concrete directly stems from my enjoyment of your undergraduate course.

To Professors Ayhan Irfanoglu and Mete Sozen, thank you for serving on my graduate committee and providing me with valuable insights and experiences on this project.

Much gratitude is owed to Cheng Song who has helped me review and discuss my numerical models and research.

I would like to thank Brian Rohler and Anup Mohan at NEEScomm for their help with running OpenSees on the NEEShub. The modeling assistance from Panagliotas Galanis and Majid Baradaran Shoraka has been valued greatly.

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ABSTRACT

Skok, Nicholas R. M.S.C.E., Purdue University, December 2014. Evaluation of Collapse Indicators for Seismically Vulnerable Reinforced Concrete Buildings. Major Professor: Santiago Pujol.

Older reinforced concrete buildings can be prone to column shear and compression failures during earthquakes because of inadequate transverse reinforcement. Cities in seismic areas still have large inventories of older and potentially deficient buildings. To analyze every building and estimate its vulnerability in detail is costly. A simple method to rank quickly older buildings according to their seismic vulnerability is needed to help engineers prioritize the use of resources for rehabilitating the most vulnerable buildings.

Four indicators of building damage or collapse were evaluated using numerical analysis and prior data from building surveys: column index (Hassan and Sozen, 1997), R factor, ratio of column shear capacity to plastic shear demand, and ratio of column moment capacity to beam moment capacity. Idealized building frames were studied using nonlinear numerical analysis. Numerical models of these building frames with different spans, column sizes, numbers of floors, and transverse reinforcement ratios were analyzed with 44 ground motion records. Each numerical analysis used an algorithm to estimate whether a hypothetical building represented by a numerical model was likely to be severely damaged by strong ground motion.

Among the four indicators studied, the column index was observed to be 1) the simplest and 2) the one with the best correlation with estimates of vulnerability to damage. Approximately 3/5 of the hypothetical building frames represented by numerical models with column indices not exceeding 0.2% were classified as buildings likely to be severely damaged by strong ground motion. Buildings with column indices not exceeding 0.2% were 2 to 4 times more likely to be classified as having severe

damage than those with column indices exceeding 0.2% for ground motions with PGVs between 40 cm/s and 120 cm/s. The prior building surveys supported these observations.

1. INTRODUCTION

1.1 Background

Older reinforced concrete buildings were not always designed to prevent failure of columns in shear and compression. Code provisions to help designers prevent shear and compression failures were not published until the early 1970s. Inventories of older reinforced concrete buildings not satisfying these guidelines exist in seismic regions in the United States and elsewhere. The Concrete Coalition has estimated that there are approximately 17,000 reinforced concrete buildings vulnerable to failure in the most seismic regions of California (EERI, 2011). Identifying the most vulnerable buildings among these 17,000 structures is an urgent challenge.

A structural assessment is required to determine if a building poses a large risk to its occupants. Engineers may inspect and run numerical analyses to evaluate a building. Building details are required to construct numerical models, and this information may be unavailable to engineers. In regions with large sets of vulnerable buildings, it is too cumbersome for engineers to inspect and analyze each building. A simple method to identify the most vulnerable buildings is required. Collapse indicators are simple measures to help engineers identify the most critical structures. Within this subset of vulnerable buildings, engineers can then perform detailed analyses to prioritize the use of resources for building rehabilitation.

1.2 Objective

The objective of this study is to evaluate simple collapse indicators that engineers can use to identify the most vulnerable reinforced concrete buildings in an inventory. This report focuses on evaluating four indicators: column index (Hassan and Sozen, 1997), R factor, ratio of column shear capacity to plastic shear demand, and ratio of column moment capacity to beam moment capacity. Appendix A discusses alternative building measures.

1.3 Scope

Thirty numerical models representing hypothetical reinforced concrete building frames were used to represent a large inventory of buildings. Each numerical model was studied using nonlinear analysis with 44 strong ground motions. The software package OpenSees (PEER, 2013) was used for analysis. Analysis cases were classified as cases with severe damage if a minimum of one column shear or compression failure was estimated to have occurred. The numerical models included nonlinear spring elements calibrated to estimate occurrences of shear and compression column failures using the formulations described in Section 3.3. The numerical frame models had the following properties:

- Two- and four-stories with four bays (Figures 3.1 and 3.2)
- Span lengths (L_{span}): 12, 15, 20, 25, and 30 feet (Note: The spans of 12 and 15 feet were unrealistic for some numerical models but were used to generate a broad range of indicator values.)
- Concrete compressive strength (f'_c): 4000 psi
- Uniform distributed floor weight: 165 psf
- Nominal longitudinal reinforcement yield stress (f_y): 60 ksi
- Nominal transverse reinforcement yield stress (f_{yt}): 60 ksi
- Square column sections: 18, 24, and 30 inches square
- Column longitudinal reinforcement ratios (ρ): 0.7, 1.1, and 2.0%
- Column transverse reinforcement ratios (ρ_t): 0.06, 0.08, and 0.10%

- Column transverse reinforcement spacing (s): 12 inches
- Column axial loads: 0.01 through 0.46 $f'_c A_g$
- Beam cross-section (b and h): 18 by 28 inches
- Beam longitudinal reinforcement ratios (ρ' and ρ): 0.9% near the top and 0.5% near the bottom
- Beam transverse reinforcement ratio (ρ_t): 0.15%

The following modeling assumptions were used in the numerical models:

- Two-dimensional planar models
- Rigid foundation
- Rayleigh damping using 2% of critical damping
- Lumped plasticity for beam and column elements
- Beam and column elements connected with rigid joint with lengths equal to half of the section height
- Cracked beam section moment of inertia equal to 60% of cross-sectional moment of inertia
- Cracked column section moment of inertia equal to 30% of cross-sectional moment of inertia
- Concentrated axial loads based on tributary area of the columns (Figure 3.4)
- Nonlinear flexural behavior using a Clough moment-rotation formulation with hysteresis implemented by Ibarra et al. (2005) (Figures 3.8 and 3.9)
- Elwood and Moehle (2003) formulation for estimating capacities and drifts at failure for shear and compression in columns.
- Strong ground motions with PGVs between 40 and 120 cm/s

2. DESCRIPTION OF COLLAPSE INDICATORS

2.1 Introduction

For large inventories of older buildings, the time and effort required for engineers to evaluate thoroughly each building is prohibitive. Simple parameters are required to evaluate the risk of older reinforced concrete buildings. Collapse indicators are simple measures of a structure that can be used to rank buildings according to their vulnerability. This study considers four collapse indicators: column index, R factor, ratio of column shear capacity to plastic shear demand, and ratio of column moment capacity to beam moment capacity. Appendix A discusses alternative building measures. A combination of indicators may be able to identify critical buildings within a deficient building inventory.

2.2 Column Index

Hassan and Sozen (1997) developed the column index for monolithic, reinforced concrete buildings based on their seismic vulnerability. The column index was calibrated after the 1992 Erzincan earthquake as part of the priority index. The priority index includes a term to consider the presence of walls. Because this study focused on reinforced concrete frames, only the column index was applicable.

The column index is calculated using half of the total cross-sectional area of all columns in the first story divided by the total floor area above ground floor area (Equation 2.1). As the column index increases, the stiffness and strength increases for a building. This indicator is attractive because its calculation is quick and requires minimal information about a structure.

$$CI = \frac{1}{2}\frac{A_{col}}{\Sigma A_{fl}} \tag{2.1}$$

The column index was evaluated by building surveys after events in Erzincan (Hassan and Sozen, 1997), Duzce (Donmez and Pujol, 2005), Bingol (Ozcebe et al., 2003), Peru (DataHub, 2014), Wenchuan (Zhou et al., 2013), and Haiti (O'Brien et al., 2011). Surveyed buildings were ranked as either having reinforced concrete elements with light, moderate, or severe damage. Light damage was assigned to structures with hairline cracks in structural members. Moderate damage was defined as spalling of concrete. Buildings with member failures were classified as severely damaged. The column indices were calculated from drawings or field measurements of the buildings.

This report combined previous building surveys and excluded buildings with masonry or reinforced concrete structural walls. From the combined surveys, Figure 2.1 shows the percentages of buildings classified as severely damaged versus column index. The percentage of severely damaged buildings decreased as the column index increased. 3/5 of buildings with column indices not exceeding 0.2% were classified as having severe damage. Buildings with column indices not exceeding 0.2% were twice as likely to be classified as having severe damage than buildings with column indices exceeding 0.2%.

2.3 R factor

Engineers estimate the design lateral loads induced by strong ground motion for a structure by using its weight and design acceleration. The design acceleration is computed from a design spectrum for a single degree of freedom system (SDOF). Design forces are reduced to levels deemed appropriate by professional consensus by using "R factor". In this study, for the numerical models representing the hypothetical buildings described in Section 3, the R factor is computed with Equation 2.2. In it, base shear strength is V_{max}, building weight is W_b, and linear spectral acceleration is S_a (g).

$$R = \frac{S_a(T_1) \times W_b}{V_{max}} \tag{2.2}$$

V_{max} was computed for each numerical building model using a nonlinear limit analysis with an assumed triangular lateral load distribution. The weight of each hypothetical frame (Section 3.2) was used for W_b. The spectral acceleration for each numerical model was computed using a linear spectrum for the 44 ground motion records described in Section 3.4 and the following procedure:

1. Compute the uncracked fundamental period for each numerical building model.
2. Generate the 44 acceleration spectra for the ground motion records in Section 3.4 using SDOFs with 2% of critical damping.
3. Create an acceleration spectrum by computing the mean plus one standard deviation of the 44 spectral accelerations at each SDOF period.
4. Find the S_a from the spectrum created in (3) using the period calculated in (1).

Using R factor in an evaluation presumes knowledge about the anticipated ground motions and requires a detailed structural analysis. Detailed building drawings may not always be available to engineers but are necessary for a structural analysis.

2.4 Ratio of Column Shear Capacity to Plastic Shear Demand

The column shear capacity to column shear demand ratio, V_n/V_p, is an indicator of whether a column is vulnerable to shear failure. Values less than one indicate that a column does not have enough capacity to develop flexural plastic hinges. The V_n/V_p ratio is calculated for all of the columns in the numerical models representing hypothetical buildings described in Section 3.2.

The column shear capacity (V_n) was computed using equations for nominal shear strength provided by ACI 318-11 (Equation 2.3). In it, N_u is the axial load, A_g is the gross cross-sectional area, f'_c is concrete compressive strength, b_w is the width of the section, A_{sh} is the cross-sectional area of the transverse reinforcement, f_{yt} is the yield strength of the transverse reinforcement, d is the distance from extreme compression fiber to centroid of longitudinal steel, and s is the spacing of the transverse reinforcement.

$$V_n = 2\left(1 + \frac{N_u}{2000A_g}\right)\sqrt{f_c'}b_w d + \frac{A_{sh} f_{yt} d}{s} \tag{2.3}$$

The plastic shear demand for each column was calculated using $V_p = 2M_p/h$. Plastic moment capacity (M_p) of a column was assumed to be 1.2 times the yield moment. The yield moment was computed using the program FLECHA (Pujol and Villalobos, 2014) and the assumptions discussed in Section 3.2. The clear height of each column was h.

The V_n/V_p ratio was extended to represent vulnerability of the numerical models representing hypothetical building frames using a procedure proposed in ATC-78 (ATC, 2011). This study defined the term as α, and its value was computed as follows:

1. Calculate V_n/V_p for all the columns in a numerical model.
2. Determine the average V_n/V_p for each story.
3. Select the minimum value from (2) for α.

The parameter α is a simplified indicator to rank the vulnerability of a building to column shear failures. Computing α requires the knowledge of sizes, placement, and material properties of the longitudinal and transverse reinforcing steel in the columns. This information may be unavailable or difficult to obtain for a large inventory of older buildings.

2.5 Ratio of Column Moment Capacity to Beam Moment Capacity

ACI 318-11 calls for each joint in a frame to have a column moment capacity to beam moment capacity ratio, $\Sigma M_c/\Sigma M_b$, larger than 6/5. This requirement aims to enforce the "strong-column weak-beam" design idea where hinging occurs mostly in the beams to avoid weak stories.

The column moment capacity to beam moment capacity ratio was calculated for the joints in the studied numerical models. ΣM_c was the sum of the nominal column moment capacities at the face of the joint. Column moment capacities were calculated using FLECHA (Pujol and Villalobos, 2014) and axial loads caused by gravity. ΣM_b was the sum of the nominal beam capacities at the joint face. Slab contributions to the beam moment capacity were neglected.

The ratio of column moment capacity to beam moment capacity can vary for each joint in a building. ATC-78 (ATC, 2011) proposed a procedure to use this indicator to represent an entire building. This study defined the term as β, and its value was computed as follows:

1. Compute the $\Sigma M_c/\Sigma M_b$ for the joints at each floor in a numerical model except the roof.
2. Determine the average $\Sigma M_c/\Sigma M_b$ for each floor.
3. Select the minimum value from (2) for β.

The parameter β is a simplified indicator used to estimate the vulnerability of a building for developing weak stories. $\Sigma M_c/\Sigma M_b$ requires knowledge about the longitudinal reinforcement for columns and beams. Drawings with this information may not be available for older reinforced concrete buildings in a large inventory.

3. NUMERICAL MODELS

3.1 Introduction

Building inventories can potentially have thousands of older reinforced concrete structures. These buildings have variety of configurations and properties. To represent these variations, numerical models of idealized building frames with different numbers of stories, column sizes, and span lengths, and transverse reinforcement ratios were studied.

3.2 Description of Models

To evaluate the four collapse indicators described in Chapter 2, 30 numerical models representing hypothetical building frames were analyzed in the software package OpenSees (PEER, 2013). The numerical models represented two- and four-story frames with different column sections, span lengths, and transverse reinforcement ratios. The numerical models were designated using three characters "SX-X". The second character was the number of stories. The third character identified the model number. Tables 3.1 and 3.2 summarize the properties and modeling assumptions for the numerical models.

The hypothetical frames had four bays with equal span lengths (Figures 3.1 and 3.2). Five span lengths were considered: 12, 15, 20, 25, and 30 feet. These lengths refer to the distance between column centerlines. (Note: The spans of 12 and 15 feet are unrealistic but were used to generate a broad range of indicator values.) The tributary width for each frame was assumed to be equal to its span length. The frames had three square column sections: 18, 24, and 30 inches square. The same column section was used for all stories (Figures 3.1 and 3.2). The concrete compressive strength was assumed to be 4000 psi.

Each column section had three layers of #8 Gr. 60 bars for longitudinal reinforcement and #3 Gr. 60 ties with two legs in each direction spaced at 12 inches on center (Figure 3.3). Table 3.3 lists the cross-sectional properties for the column sections. Column axial gravity loads were computed using a uniformly distributed load of 165 psf and the tributary area for a column (Figure 3.4). The columns had axial gravity loads between 1% and 46% $P/(A_g f'_c)$ (Tables B.1 - B.30).

One beam section was used in the numerical models (Figure 3.5). The beam section had 5-#8 Gr. 60 longitudinal bars near the top and 3-#8 Gr. 60 longitudinal bars near the bottom. The beam had #4 Gr. 60 stirrups with two legs spaced at 10 inches on center. Table 3.3 lists a complete set of section properties for the beam.

Nonlinear flexural behavior was modeled using rotational springs at the ends of linear beam and column elements (Figures 3.6 and 3.7). The column elements had an additional horizontal and vertical spring to model shear and axial failures (Figure 3.6). The rotational springs followed the hysteresis model proposed by Clough and implemented by Ibarra et al. (2005) (Figures 3.8 and 3.9). This was defined by using yield moment (M_y), plastic moment (M_p), plastic rotation (θ_p), post-capping rotation (θ_{pc}), cyclic deterioration (λ), and residual moment (M_{res}). The parameters for each numerical model are listed in Tables B.1 - B.30.

In this study, yield moments were calculated at the point of first yielding in the steel for beam and column cross-sections. The yield moments were calculated using the program FLECHA (Pujol and Villalobos, 2014) and section properties in Table 3.3. Yield moments for the columns were calculated considering axial gravity loads. For beams and columns M_p was assumed to be $1.2M_y$.

For the columns M_{res} was set equal to M_p to maintain a plateau in the moment-rotation backbone curve (Figure 3.8). This was done to avoid numerical convergence issues with the shear spring (Section 3.3.1) discussed by Elwood and Moehle (2003). Because the columns maintained a constant plastic moment, the same values for θ_p

and θ_{pc} were used in all models for simplicity. The value λ was set as zero to enable flexural strength deterioration for the columns.

For the beams M_{res} was 10% of M_p (Figure 3.9). The beam rotations θ_p and θ_{pc} were calculated using the effective depth of the section and computed curvatures from FLECHA. The curvatures were calculated for concrete compression strains of 0.004 and 0.008 in the outermost fiber. The value for λ was selected based on a similar beam section used in ATC-78 (2011).

The linear elastic elements connecting the beam and column springs had reduced moments of inertia to account for concrete cracking. For the columns, 30% of the cross-sectional moment of inertia was used for the cracked moments of inertia as recommended by ASCE 41 (2006). For the beams, 60% of the cross-sectional moment of inertia was used for the cracked moments of inertia to account for the contribution from the slab to the beam stiffness. The modulus of elasticity was assumed to be 3600 ksi for the beam and column linear elements.

3.3 Representation of Shear and Axial Response of Columns

The addition of horizontal and vertical springs allowed the numerical models to estimate the likelihood of column shear and compression failures. Two springs are attached to the top of each column (Figure 3.6). The springs followed a formulation for shear and compression force capacities and drifts at failure proposed by Elwood and Moehle (2003). Analysis cases were classified as severely damaged if the algorithm estimated a minimum of one column shear or compression failure during a dynamic analysis. Beam shear failure was not considered.

3.3.1 Shear Response

Elwood and Moehle (2003) developed a formulation to estimate the shear capacity and drift at which a column failure occurs after plastic hinging. A shear failure is estimated to take place when the limiting shear (Equation 3.1) is exceeded in a column element. In Equation 3.1, Δ_s/l is inter-story drift ratio, ρ_t is transverse reinforcement ratio, P is axial load in the column, A_g is gross cross-sectional area, f'_c and is concrete compressive strength.

$$V_n = 500\left(A_g\sqrt{f'_c}\left(0.03 + 4\rho_t - \frac{\Delta_s}{l} - \frac{1}{40}\frac{P}{A_g f'_c}\right)\right) \tag{3.1}$$

Equation 3.1 was computed for each column considering its current drift ratio and axial load during a dynamic analysis. A shear failure was estimated to have occurred when the shear demand in a column exceeded the capacity computed by Equation 3.1. Analysis cases were classified as likely to have severe damage after a minimum of one estimated column shear failure.

3.3.2 Axial Response

Axial compression capacities and drifts at failure for columns were estimated using a formulation by Elwood and Moehle (2003). Compression in a column is transferred through shear friction after a shear failure has occurred. Equation 3.2 computes the limiting axial load where $\theta = 65°$ is the crack angle, A_{sh} is area of transverse reinforcing steel, f_{yt} is yield strength of the transverse reinforcement, d is effective depth, s is spacing of the transverse reinforcing steel, and Δ_a is inter-story drift ratio.

$$P_n = \left(\frac{1 + (\tan\theta)^2}{25\Delta_a} - \tan\theta\right)\frac{A_{sh} f_{yt} d}{s}\tan\theta \tag{3.2}$$

Equation 3.2 was computed for each column at each time-step during an analysis. A column compression failure was estimated to take place when the demand exceeded the calculated limiting axial capacity from Equation 3.2. The analysis was stopped and classified as likely to have severe damage after the capacity was exceeded.

3.4 Ground Motion Records

Numerical models representing hypothetical building frames described in Section 3.2 were analyzed using the FEMA P-695 “Far-Field” record set (ATC, 2009). This record set contained 44 ground motions summarized in Table 3.4. The ground motions were recorded from epicentral distances between 8 km and 100 km during events with magnitudes between 6.5 and 7.6. The peak ground accelerations (PGAs) varied from about 0.2 g to 0.8 g, and peak ground velocities (PGVs) were calculated to be between 15 cm/s and 115 cm/s. The linear acceleration spectra were using 2% of critical damping (Figure 3.10). These spectra were used as described in Section 2.3 to compute the R factors shown in Table 3.1 for the hypothetical building frames.

Each numerical model was analyzed using a set of 220 scaled ground motions from the FEMA P-695 “Far-Field” record set. The 44 records were scaled using multiples of 1.0, 1.5, 2.0, 2.5, and 3.0 times the original acceleration. These scale factors were used so that numerical models were analyzed with a range of PGVs for each record. The analysis procedure is discussed in Section 4.1.

4. EVALUATION OF INDICATORS

4.1 Introduction

The four collapse indicators described in Chapter 2 were evaluated in this chapter: column index, R factor, column moment capacity to beam moment capacity, and column shear capacity to plastic shear demand. Alternative indicators are discussed in Appendix A. This evaluation was done using the results from dynamic analyses of the hypothetical building models described in Chapter 3. Each numerical model was analyzed using a set of 220 ground motion records described in Section 3.4. Each analysis was conducted until:

1. the end of the record was reached, or
2. a column shear or compression failure as defined in Section 3.3 was estimated to have occurred by the algorithms described in Sections 3.3.1 and 3.3.2.

All cases in which estimated column shear or compression failures were computed by the algorithm were classified as instances of building responses that were more likely to exhibit severe damage or collapse. To organize all analysis results a parameter, called the Mean Collapse PGV, was defined as follows:

1. For each of the 44 records used, select the minimum scale factor (see Section 3.4) leading to an instance of severe damage for a given numerical building model.
2. Compute the PGV for the 44 scaled versions of the records selected in (1) using the corresponding scale factor.
3. Calculate the mean of the 44 values of PGV from (2).

Each numerical model representing an instance of a hypothetical building structure (with a fixed number of stories, span length, etc.) was associated with a single

Mean Collapse PGV. Correlation between Mean Collapse PGV and a given collapse indicator was interpreted to suggest that the indicator can help identify vulnerable structures. Additionally, the percentage of analysis instances in which estimated shear or compression failures of columns occurred was also used to evaluate the collapse indicators. This was achieved by:

1. Remove analysis instances where the scale factor produced PGVs outside of 40 cm/s $<$ PGV $\leq$ 120 cm/s for all cases. (This is the range of PGV for the field data described in Section 2.2)

2. Group analysis cases with similar collapse indicators into statistical bins

3. Divide the number of cases with severe damage by the number of analysis cases for each bin in (2).

Earthquakes with PGVs exceeding 120 cm/s were viewed as infrequent, so analysis cases with PGVs exceeding 120 cm/s were not considered. A lower bound of 40 cm/s was used to exclude moderate and light ground motions. Item 3 was used to identify the percentage of severely damaged cases for hypothetical models within a collapse indicator bin. Table 4.1 displays a summary of the analysis results. A total of 1592 cases were classified as instances of severe damage out of 4560 cases.

4.2 Column Index

The column index (Section 2.2) proposed by Hassan and Sozen (1997) was evaluated using the numerical models representing hypothetical buildings and previous building surveys described in Section 2.2. Figure 4.1 plots the Mean Collapse PGV versus column index. As the column index increased, the Mean Collapse PGV increased. The Mean Collapse PGV of the numerical models increased faster for column indices between 0% and 0.2%. That is, Mean Collapse PGV was more sensitive to column indices less than 0.2%, so focusing resources for rehabilitation on this range may likely yield the greatest benefit.

Figure 4.2 shows a plot of the percentage of numerical building models and field cases (see Section 2.2) classified as instances of severe damage versus column index. The percentage of numerical building models classified as vulnerable to severe damage decreased as column index increased. Numerical models representing hypothetical buildings with column indices not exceeding 0.2% were classified as likely to have severe damage in approximately 3/5 of the analysis cases. Models with column indices not exceeding 0.2% were 4 times more likely to be classified as having severe damage than those with column indices exceeding 0.2%. The prior building surveys described in Section 2.2 showed a similar decreasing percentage of buildings classified as likely to have severe damage as column index increased. Nearly 3/5 of surveyed buildings with column indices not exceeding 0.2% were classified as having severe damage. Buildings with column indices not exceeding 0.2% were twice as likely to be classified as having severe damage than buildings with column indices exceeding 0.2%.

The numerical model and field data both showed that column index can be used to rank buildings by seismic vulnerability. Buildings with column indices not exceeding 0.2% may be studied in detail first with an emphasis on the buildings with the lowest column indices and any captive columns. O'Brien et al. (2011) observed increases in the likelihood of severe damage for buildings with captive columns.

4.3 R Factor

The R factor described in Section 2.3 was evaluated exclusively using the numerical analyses of the models representing hypothetical building frames. The available field data did not have the required detail for its use in evaluating 1/R. The inverse of the R factor (1/R) was compared with the numerical results to determine whether lower indicator values of 1/R corresponded to hypothetical building models which were most likely to be vulnerable to severe damage. Figure 4.3 plots Mean Collapse PGV versus 1/R. The Mean Collapse PGV increased as 1/R increased.

Figure 4.4 shows a plot of the percentage of analysis cases for numerical building models classified as likely to have severe damage versus 1/R. The percentage of analysis cases classified as likely to have severe damage decreased as 1/R increased. Nearly 3/5 of analysis cases for numerical models representing frames with 1/R not exceeding 0.2 were classified as likely to have severe damage. Cases for numerical models with 1/R not exceeding 0.2 were 3 times more likely to be classified as having sever damage than analysis cases for numerical models with 1/R exceeding 0.2.

Figure 4.5 plots 1/R and column index for the numerical models representing hypothetical buildings. Each numerical building model was assigned a data marker which represented the percentage (out of 152 cases) that were classified as vulnerable to severe damage. This plot was used to determine if 1/R can be used to eliminate analysis cases for buildings models with column indices not exceeding 0.2% and not likely to have severe damage ("false positives"). Figure 4.5 shows a linear trend between 1/R and column index for the numerical building models studied. This was inferred to mean that 1/R and column index can be used to produce the same ranking of the most vulnerable buildings in an inventory of older reinforced concrete buildings. Nearly 2/3 of analysis cases representing hypothetical buildings with 1/R not exceeding 0.2 and column index not exceeding 0.2% were classified as likely to have severe damage.

The numerical models of hypothetical buildings showed that 1/R can be used to rank building vulnerable in an inventory of older reinforced concrete buildings. Using 1/R with column index identified a larger percentage of damaged numerical models than column index alone. However, the R factor requires detailed drawings and structural analyses for its calculation as described in Section 2.3. Computing the column index is simpler and its use would be less expensive.

4.4 Ratio of Column Shear Strength to Plastic Shear Demand

Ratio of column shear strength to plastic shear demand was represented using α (Section 2.4) and evaluated using the numerical analysis results. The available field data did not have the required detail for its use in evaluating α. Figure 4.6 plots the Mean Collapse PGV versus α. The Mean Collapse PGV increased as α increased. Numerical building models associated with α not exceeding 1.1 were more sensitive to Mean Collapse PGV than cases with values of α exceeding this limit.

The percentage of analysis cases for hypothetical frames classified as vulnerable to severe damage versus α is shown in Figure 4.7. As α increased, the percentage of analysis cases classified as likely to have severe damage decreased. Approximately 2/3 of analysis cases for numerical models representing frames with α not exceeding 1.1 were classified as likely to have severe damage. Numerical models with α not exceeding 1.1 were 4 times more likely to be classified as vulnerable to severe damage than numerical models with α exceeding 1.1.

Figure 4.8 is a plot of α and the column index for the numerical models representing hypothetical buildings. Each numerical model was assigned a data marker which represented the percentage (out of 152 cases) classified as vulnerable to severe damage. This plot was used to determine if α could be used to eliminate model instances of hypothetical frames in which column indices were less than 0.2% and classified as not likely to experience severe damage ("false positives"). 7/10 of the analysis cases representing hypothetical buildings with α not exceeding 1.1 and column index not exceeding 0.2% were classified as vulnerable to severe damage.

The numerical results suggest that α can be used to rank building vulnerability in an inventory of older reinforced concrete buildings. Using α with column index identified a larger percentage of severely damaged numerical models than column index alone. The parameter α should be considered after an initial filtering of a building inventory based on column index.

4.5 Ratio of Column Moment Strength to Beam Moment Strength

Ratio of column moment strength to beam moment strength was represented here as β (Section 2.5) and was evaluated exclusively using the numerical analyses of the hypothetical building models. The available field data did not have the required detail for its use in evaluating β. Figure 4.9 plots Mean Collapse PGV versus β. There were three distinct sets of points. Each set corresponded to hypothetical building models with the same column size (18, 24, and 30 inches square). Each set showed a decrease in the Mean Collapse PGV as β increased. This trend corresponded with increases in building spans for the same column sizes. More axial load was sustained in the columns as the span increased, so the column moment strength increased. Additionally, frames had to resist more inertia as the spans increased, so the Mean Collapse PGVs decreased.

Figure 4.10 shows the percentage of numerical building models classified as likely to have severe damage versus β. There was not a clear trend between the percentage of hypothetical buildings classified as likely to have severe damage and β. Column moment capacity to beam moment capacity was not an efficient indicator of seismic vulnerability for the studied hypothetical building frames.

5. CONCLUSIONS

Four collapse indicators were evaluated using numerical analysis to determine their efficiency in identifying the most seismically vulnerable reinforced concrete buildings from a large inventory of older structures. Numerical models represented hypothetical building frames with different span lengths, column sizes, numbers of floors, and transverse reinforcement ratios. The considered ranges are listed in Table 3.1 and Section 1.3. The collapse indicators considered were: column index (Hassan and Sozen, 1997), R factor, ratio of column shear capacity to plastic shear demand, and ratio of column moment capacity to beam moment capacity.

Out of the four indicators evaluated, the column index was observed to be the simplest, and the one with the best correlation with estimates of vulnerability to damage.

For strong ground motions with PGVs betwen 40 cm/s and 120 cm/s, approximately 3/5 of the numerical models representing hypothetical buildings with column indices not exceeding 0.2% were classified as likely to have to severe damage. Models with column indices not exceeding 0.2% were 4 times more likely to be classified as likely to have severe damage than those with column indices exceeding 0.2%. Field data from prior building surveys also showed that nearly 3/5 of building frames with column indices not exceeding 0.2% were classified as having severe damage. Buildings with column indices not exceeding 0.2% were twice as likely to have severe damage than those with column indices exceeding 0.2%.

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TABLES

Table 3.1: Properties for the hypothetical building models

Model	L_{span} (ft)	b_{col} (in)	Stories	T_1 (s)	W_b (kip)	V_{max} (kip)	CI (%)	R	α	β
S2-0	12	18	2	0.22	190	188	0.49	1.7	1.23	0.62
S2-1	15	18	2	0.28	297	201	0.31	2.6	1.19	0.65
S2-2	20	18	2	0.38	528	223	0.18	3.7	1.04	0.75
S2-3	25	18	2	0.49	825	219	0.11	6.6	1.04	0.78
S2-4	30	18	2	0.61	1188	225	0.08	7.2	1.02	0.83
S2-5	12	24	2	0.14	190	278	0.87	1.0	1.38	0.91
S2-6	15	24	2	0.18	297	286	0.56	1.6	1.36	0.94
S2-7	20	24	2	0.26	528	301	0.31	3.2	1.30	1.02
S2-8	25	24	2	0.34	825	308	0.20	4.6	1.25	1.08
S2-9	30	24	2	0.42	1188	317	0.14	6.4	1.16	1.18
S2-10	12	30	2	0.14	190	349	1.36	1.2	1.59	1.18
S2-11	15	30	2	0.20	297	352	0.87	2.5	1.55	1.24
S2-12	20	30	2	0.27	528	357	0.49	4.0	1.49	1.32
S2-13	25	30	2	0.34	825	366	0.31	5.4	1.38	1.42
S2-14	30	30	2	0.11	1188	380	0.22	0.7	1.26	1.56
S4-0	12	18	4	0.40	380	220	0.24	2.8	1.02	0.71
S4-1	15	18	4	0.51	594	214	0.16	4.9	1.02	0.73
S4-2	20	18	4	0.71	1056	220	0.09	5.9	0.99	0.75
S4-3	25	18	4	0.92	1650	219	0.06	7.3	1.01	0.78
S4-4	30	18	4	1.15	2376	205	0.04	7.9	0.99	0.83
S4-5	12	24	4	0.27	380	353	0.43	1.9	1.31	0.91
S4-6	15	24	4	0.35	594	307	0.28	3.3	1.24	0.94
S4-7	20	24	4	0.51	1056	282	0.16	6.6	1.12	1.02
S4-8	25	24	4	0.67	1650	288	0.10	7.4	1.03	1.08

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Table 3.1: *continued*

Model	L_{span} (ft)	b_{col} (in)	Stories	T_1 (s)	W_b (kip)	V_{max} (kip)	CI (%)	R	α	β
S4-9	30	24	4	0.85	2376	293	0.07	8.2	0.95	1.18
S4-10	12	30	4	0.21	380	321	0.68	2.0	1.47	1.18
S4-11	15	30	4	0.29	594	325	0.43	3.2	1.28	1.24
S4-12	20	30	4	0.42	1056	330	0.24	5.5	1.25	1.32
S4-13	25	30	4	0.56	1650	339	0.16	7.8	1.11	1.42
S4-14	30	30	4	0.71	2376	356	0.11	8.1	1.00	1.56

Table 3.2: Assumptions for the numerical models

Modeling Assumptions	
Type	Assumptions
Frames	- Rigid foundation - Two-dimensions with rigid joints connecting elements - Lumped-plasticity to model the behavior of the column and beam elements - Tributary width equal to span length - Weight calculated using the frame tributary area and uniform distributed load of 165 psf - 2% of critical damping using Rayleigh damping
Column Elements	- Rotational springs to model moment-rotation at the ends of a linear elastic line element - Horizontal spring to estimate shear and drift ratio at failure for columns (Elwood and Moehle, 2003) - Vertical spring to estimate axial compression and drift ratio at failure for a column (Elwood and Moehle, 2003) - Cracked moment of inertia taken as 30% of cross-sectional moment of inertia - Tributary weight applied as a concentrated load
Beam Elements	- Rotational springs to model moment-rotation at the ends of a linear elastic line element - Cracked moment of inertia taken as 60% of nominal moment of inertia

Table 3.2: *continued*

Modeling Assumptions	
Type	Assumptions
Section Properties	- Moment-rotation using a Clough model with hysteresis and parameters M_y, M_c, M_{res}, θ_p, θ_{pc}, and λ (Ibarra et al., 2005) - M_y is the moment at first steel yielding calculated using FLECHA (Pujol and Villalobos, 2014) - M_p is the plastic moment and is assumed to be equal to 1.2 times M_y - M_{res} is the residual moment and is equal to M_p for columns and $0.1M_y$ for the beams - θ_p is the plastic rotation (Figures 3.8 and 3.9) - θ_{pc} is the post-capping rotation (Figures 3.8 and 3.9) - λ is a parameter for cyclic deterioration
FLECHA	- Elastic perfectly plastic stress-strain steel relationship - Hognestad (1951) stress-strain concrete relationship

Table 3.3: Cross-sectional properties

Section	b	h	c_c	d	A_g	I_g	A_s	A'_s	ρ	ρ'	A_{sh}	s	ρ_t
	(in)	(in)	(in)	(in)	(in^2)	(in^4)	(in^2)	(in^2)	(%)	(%)	(in^2)	(in)	(%)
A	18	18	2.5	15.5	324	8748	6.32	-	2.0	-	0.22	12	0.10
B	24	24	2.5	21.5	576	27650	6.32	-	1.1	-	0.22	12	0.08
C	30	30	2.5	27.5	900	67500	6.32	-	0.7	-	0.22	12	0.06
D	18	28	2.0	26.0	504	32900	2.37	3.95	0.5	0.9	0.4	10	0.15

Table 3.4: Summary of the FEMA P-695 ground motion records

Location	Date	Epicentral Distance (km)	Mag.	Dir.	PGA (g)	PGV (cm/s)
Northridge, CA	Jan. 17, 1994	13.3	6.7	N09E N81W	0.42 0.52	59 63
Northridge, CA	Jan. 17, 1994	26.5	6.7	NS EW	0.41 0.48	43 45
Duzce, Turkey	Nov. 12, 1999	41.3	7.1	N21E S69E	0.73 0.82	56 62
Hector Mine, CA	Oct. 16, 1999	26.5	7.1	NS EW	0.27 0.34	29 42
Imperial Valley, CA	Oct. 15, 1979	33.7	6.5	S82W N08W	0.24 0.35	26 33
Imperial Valley, CA	Oct. 15, 1979	29.4	6.5	S40E S50W	0.36 0.38	34 42
Kobe, Japan	Jan. 16, 1995	8.7	6.9	NS EW	0.51 0.50	37 37
Kobe, Japan	Jan. 16, 1995	46.0	6.9	NS EW	0.24 0.21	38 28
Kocaeli, Turkey	Aug. 17, 1999	98.2	7.5	NS EW	0.31 0.36	59 46
Kocaeli, Turkey	Aug. 17, 1999	53.7	7.5	NS EW	0.22 0.15	18 40
Landers, CA	Jun. 28, 1992	86.0	7.3	NS EW	0.15 0.24	30 51

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Table 3.4: *continued*

Location	Date	Epicentral Distance (km)	Mag.	Dir.	PGA (g)	PGV (cm/s)
Landers, CA	Jun. 28, 1992	82.1	7.3	NS EW	0.28 0.42	26 42
Loma Prieta, CA	Oct. 18, 1989	9.8	6.9	NS EW	0.53 0.44	35 29
Loma Prieta, CA	Oct. 18, 1989	31.4	6.9	NS EW	0.56 0.37	36 45
Manjil, Iran	Jun. 20, 1990	40.4	7.4	NS EW	0.51 0.50	42 52
Superstition Hills, CA	Nov. 24, 1987	35.8	6.5	NS EW	0.36 0.26	46 41
Superstition Hills, CA	Nov. 24, 1987	11.2	6.5	NS EW	0.30 0.45	33 36
Cape Mendocino, CA	Apr. 25, 1992	22.7	7.0	NS EW	0.55 0.39	42 44
Chi-Chi, Taiwan	Sep. 20, 1999	32.0	7.6	NS EW	0.44 0.35	115 71
Chi-Chi, Taiwan	Sep. 20, 1999	77.5	7.6	NS EW	0.51 0.47	39 37
San Fernando, CA	Feb. 9, 1971	39.5	6.6	NS EW	0.17 0.21	15 19
Friuli, Italy	May 6, 1976	20.2	6.5	NS EW	0.35 0.31	22 31

Table 4.1: Summary of the analysis cases

Model	Collapse Indicators				Results within $40 < PGV \leq 120$ cm/s	
	CI (%)	1/R	α	β	Number of Severe Cases	Number of Cases
S2-0	0.49	0.58	1.23	0.62	21	152
S2-1	0.31	0.38	1.19	0.65	45	152
S2-2	0.18	0.27	1.04	0.75	89	152
S2-3	0.11	0.15	1.04	0.78	111	152
S2-4	0.08	0.14	1.02	0.83	132	152
S2-5	0.87	1.02	1.38	0.91	1	152
S2-6	0.56	0.62	1.36	0.94	8	152
S2-7	0.31	0.31	1.30	1.02	36	152
S2-8	0.20	0.22	1.25	1.08	60	152
S2-9	0.14	0.16	1.16	1.18	75	152
S2-10	1.36	1.40	1.59	1.18	0	152
S2-11	0.87	0.83	1.55	1.24	1	152
S2-12	0.49	0.41	1.49	1.32	10	152
S2-13	0.31	0.25	1.38	1.42	24	152
S2-14	0.22	0.19	1.26	1.56	44	152
S4-0	0.24	0.36	1.02	0.71	47	152
S4-1	0.16	0.21	1.02	0.73	60	152
S4-2	0.09	0.17	0.99	0.75	103	152
S4-3	0.06	0.14	1.01	0.78	141	152
S4-4	0.04	0.13	0.99	0.83	152	152
S4-5	0.43	0.52	1.31	0.91	10	152
S4-6	0.28	0.30	1.24	0.94	22	152
S4-7	0.16	0.15	1.12	1.02	43	152

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Table 4.1: *continued*

Model	Collapse Indicators				Results within $40 < \text{PGV} \leq 120$ cm/s	
	CI (%)	1/R	α	β	Number of Severe Cases	Number of Cases
S4-8	0.10	0.13	1.03	1.08	83	152
S4-9	0.07	0.12	0.95	1.18	119	152
S4-10	0.68	0.50	1.47	1.18	3	152
S4-11	0.43	0.31	1.28	1.24	11	152
S4-12	0.24	0.18	1.25	1.32	21	152
S4-13	0.16	0.13	1.11	1.42	41	152
S4-14	0.11	0.12	1.00	1.56	79	152

FIGURES

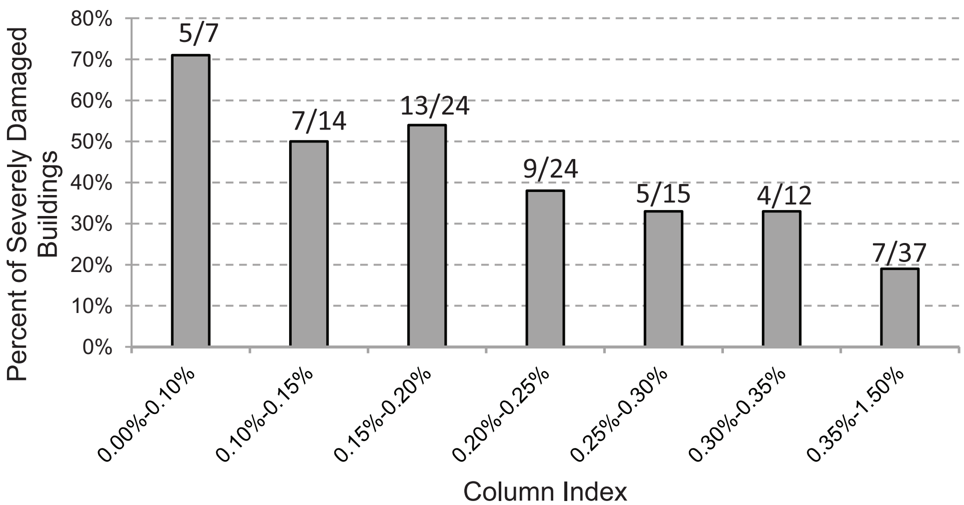


Figure 2.1: Percentage of previously surveyed buildings classified as severely damaged vs column index

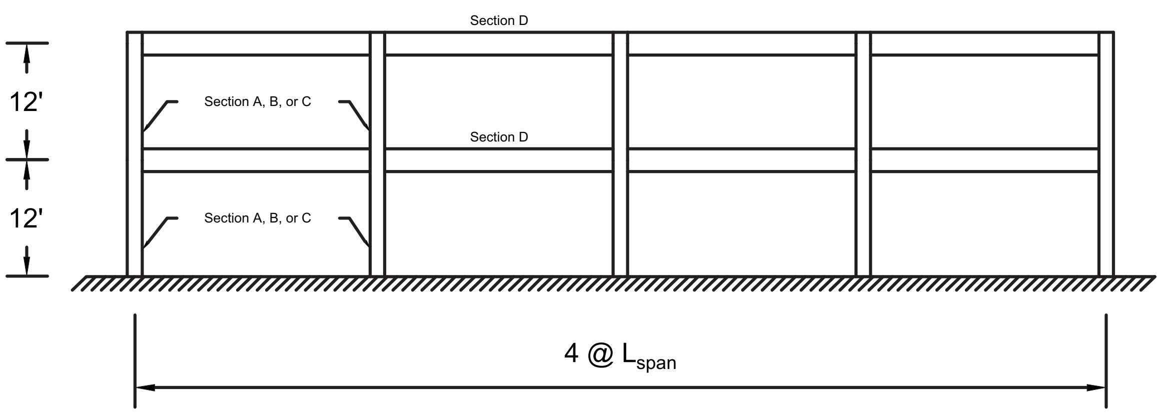


Figure 3.1: Typical two-story frame of the hypothetical building models

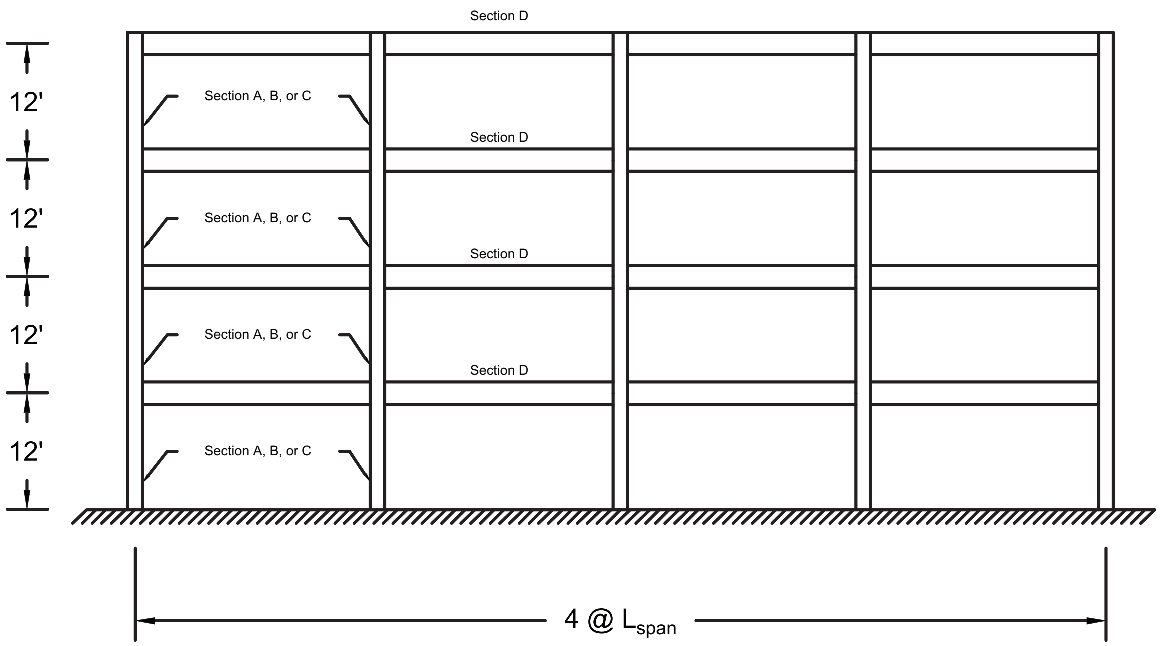
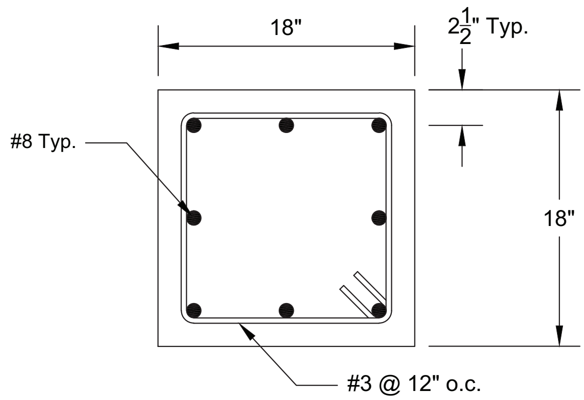
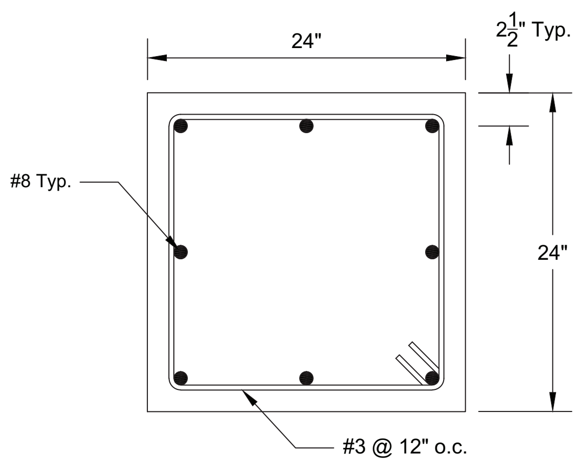


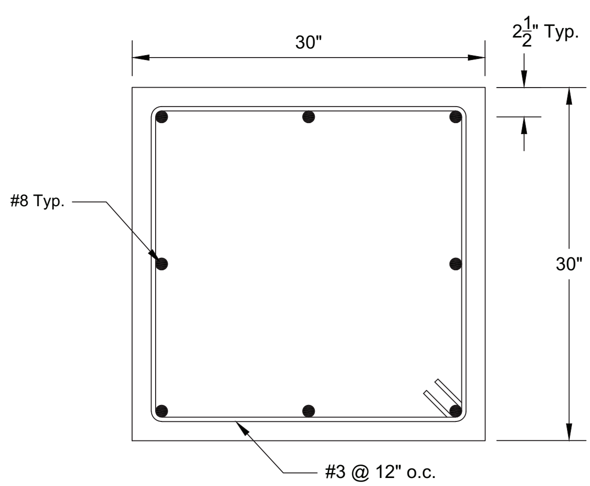
Figure 3.2: Typical four-story frame of the hypothetical building models



(a) Cross-section A

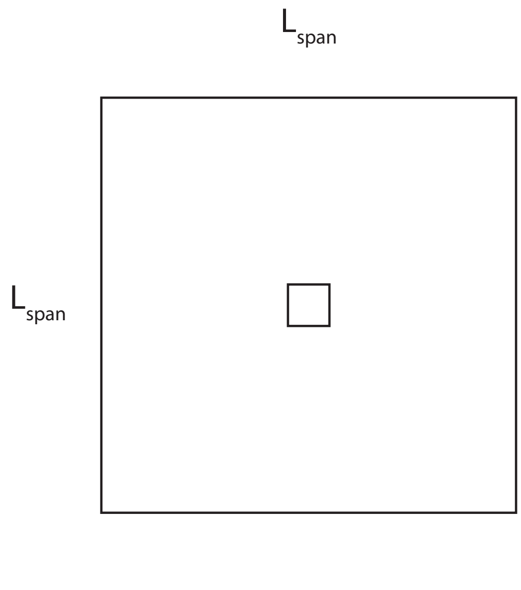


(b) Cross-section B

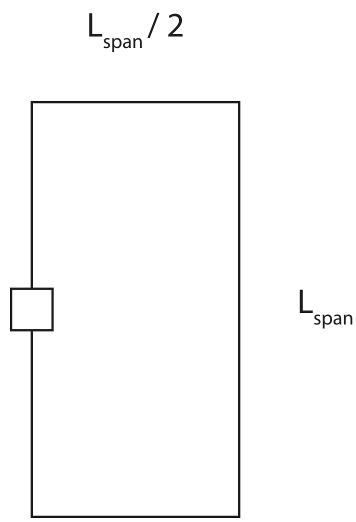


(c) Cross-section C

Figure 3.3: Column cross-sections for the hypothetical building models



(d) Interior column



(e) Exterior column

Figure 3.4: Typical tributary areas for the columns

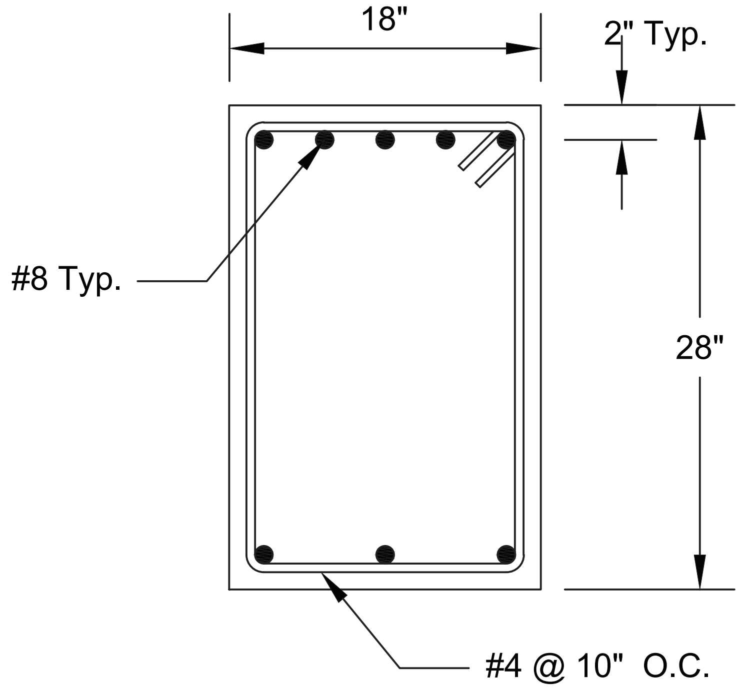


Figure 3.5: Beam cross-section D in the hypothetical building models

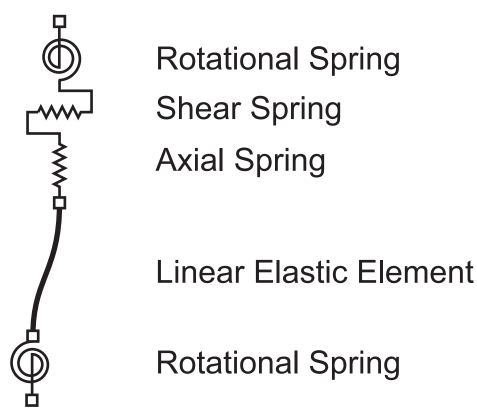


Figure 3.6: Diagram of a column element in OpenSees

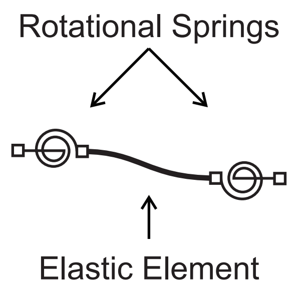


Figure 3.7: Diagram of a beam element in OpenSees

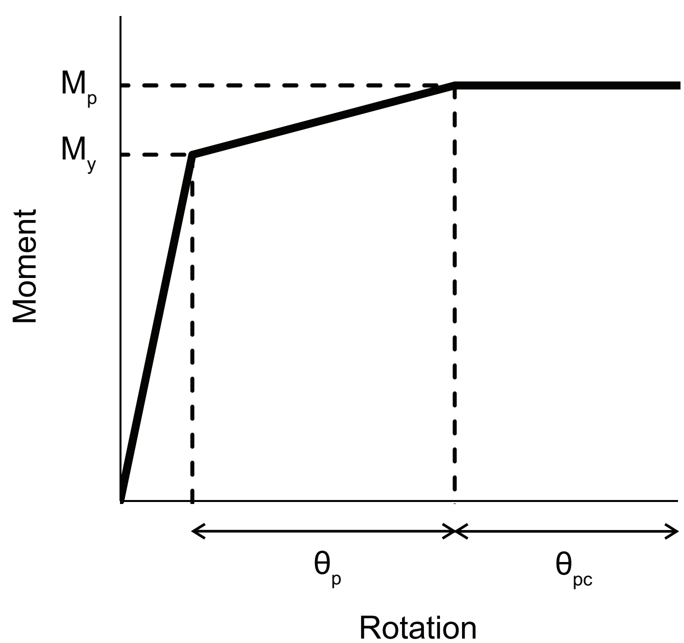


Figure 3.8: Moment-rotation backbone for column elements

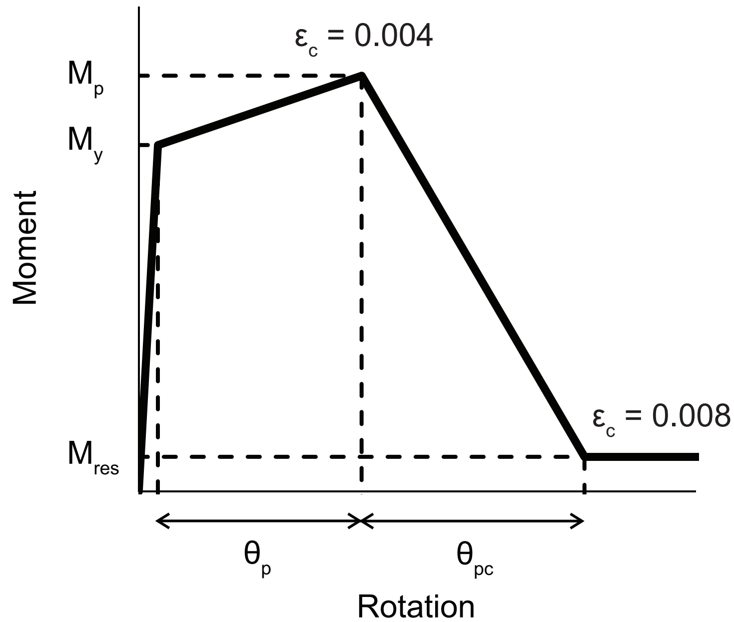


Figure 3.9: Moment-rotation backbone for beam elements

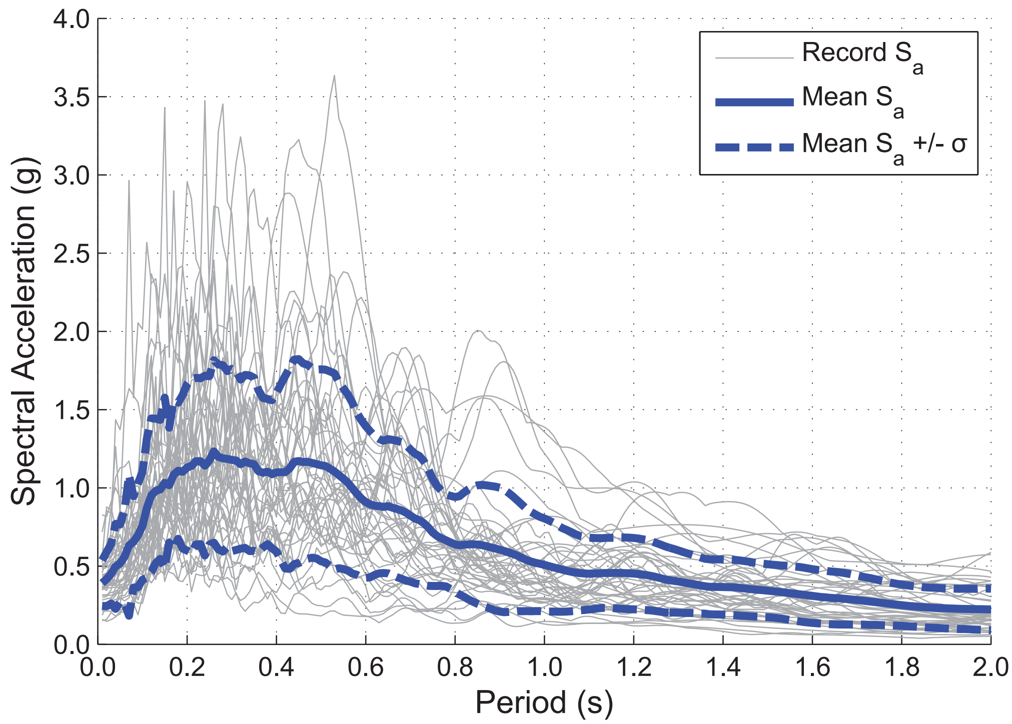


Figure 3.10: Linear acceleration spectra for the FEMA P-695 "Far-Field" ground motion records with 2% of critical damping

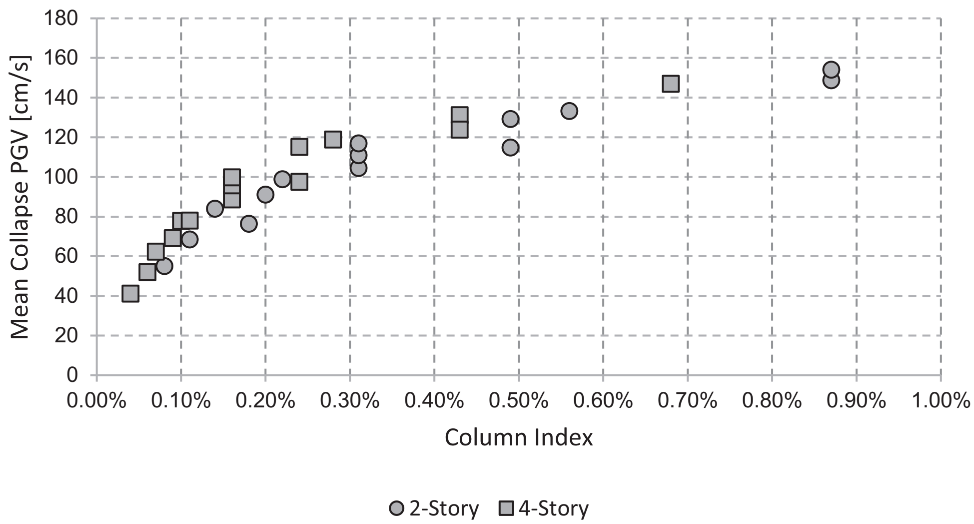


Figure 4.1: Mean Collapse PGV for the numerical building models vs column index

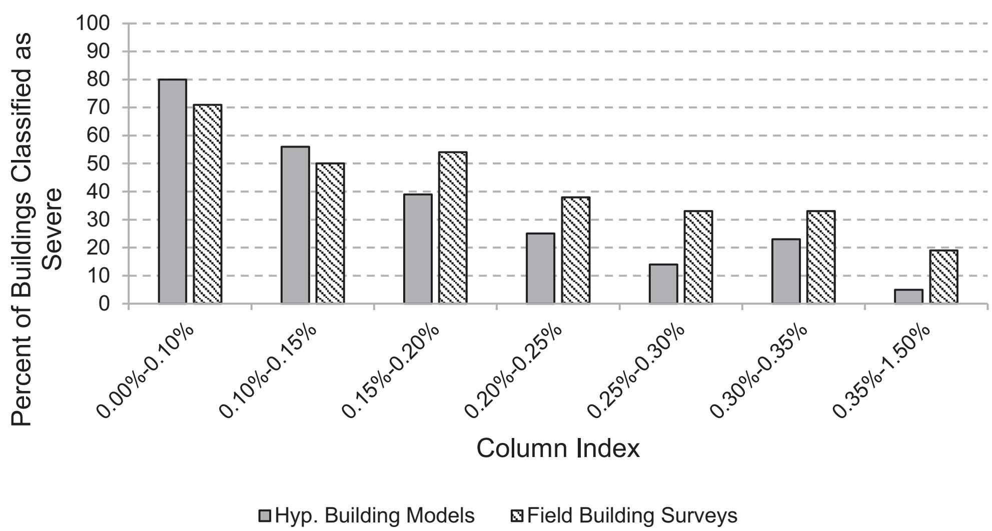


Figure 4.2: Percentage of numerical building models classified as likely to have severe damage vs column index

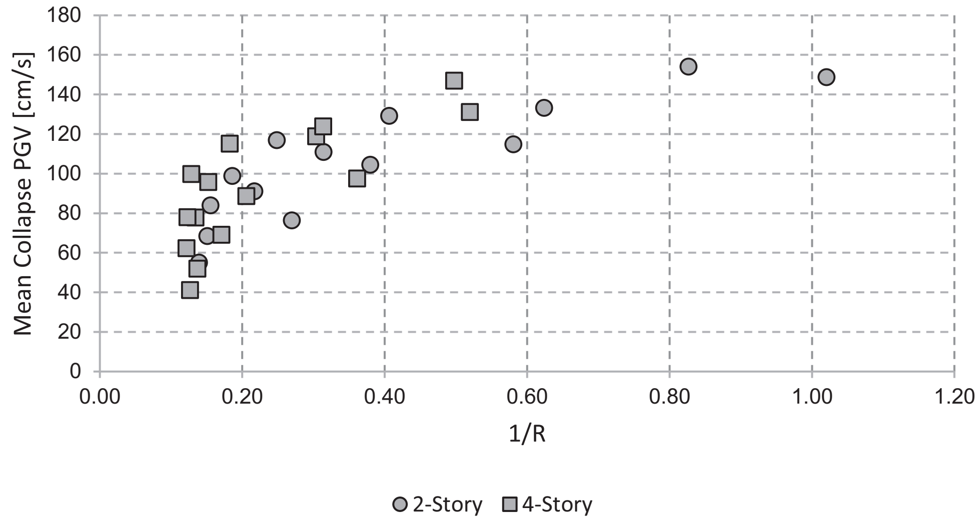


Figure 4.3: Mean Collapse PGV for the numerical building models vs 1/R

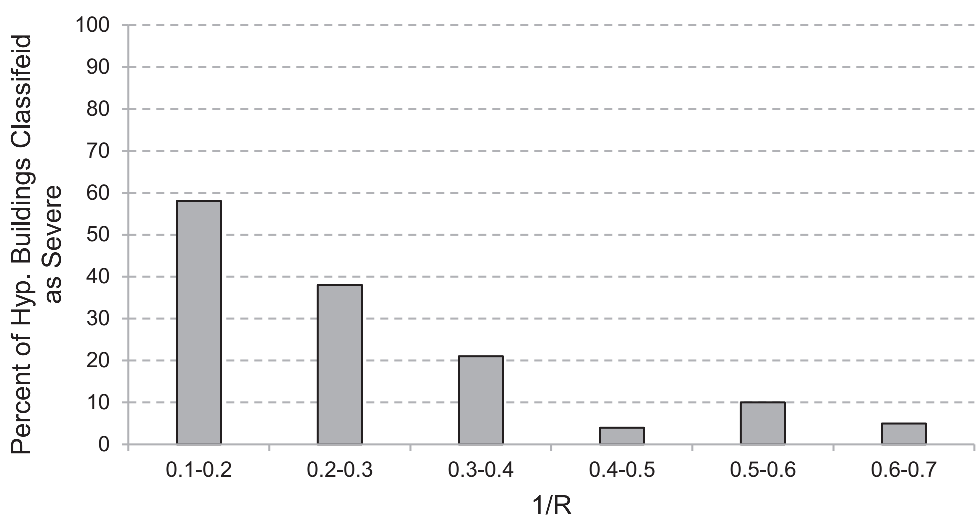


Figure 4.4: Percentage of numerical building models classified as likely to have severe damage vs 1/R

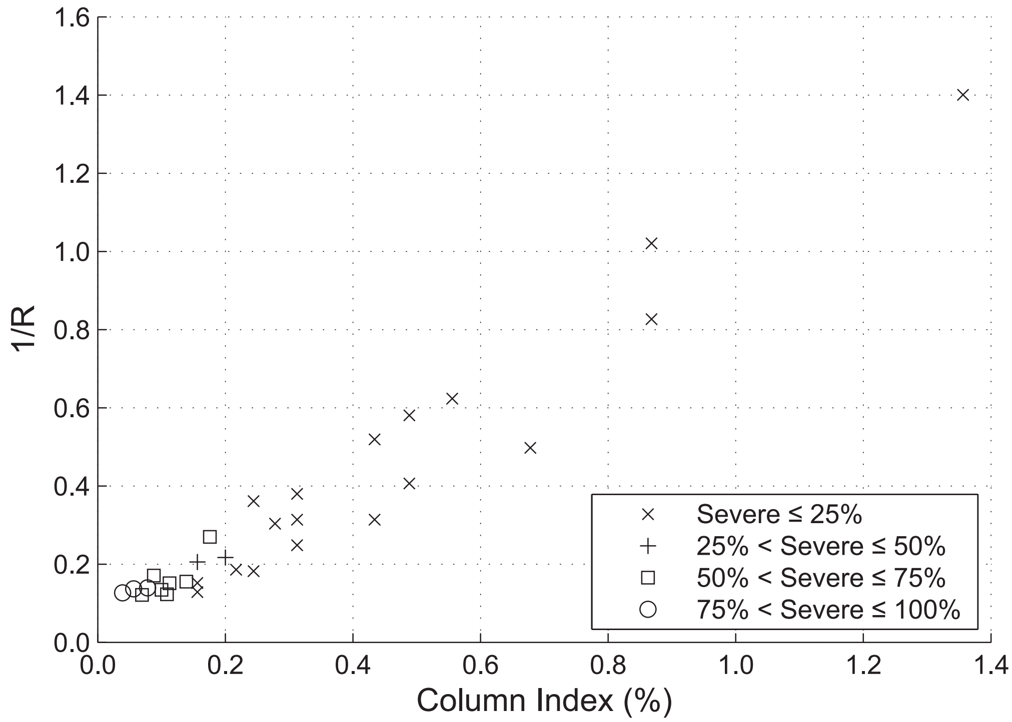


Figure 4.5: Percentage of numerical building models classified as likely to have severe damage vs 1/R and column index

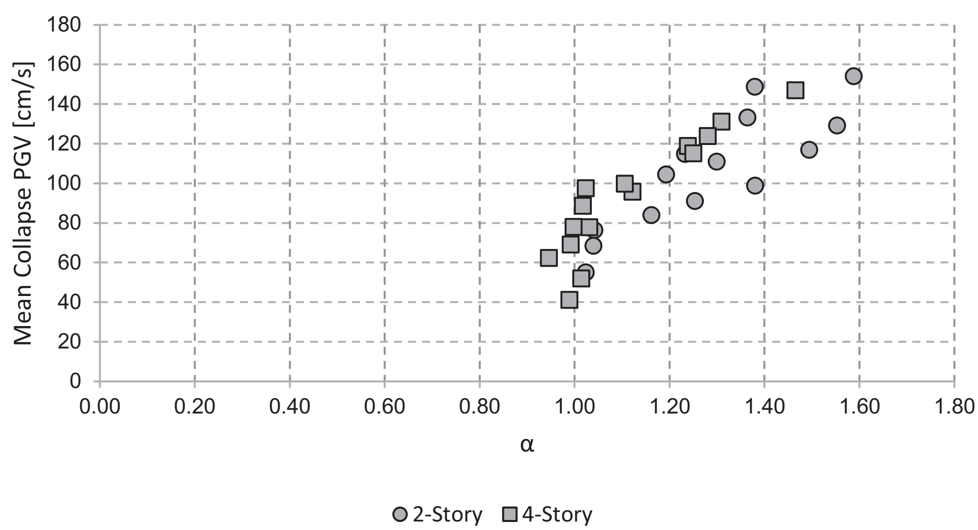


Figure 4.6: Mean Collapse PGV of the numerical building models vs α

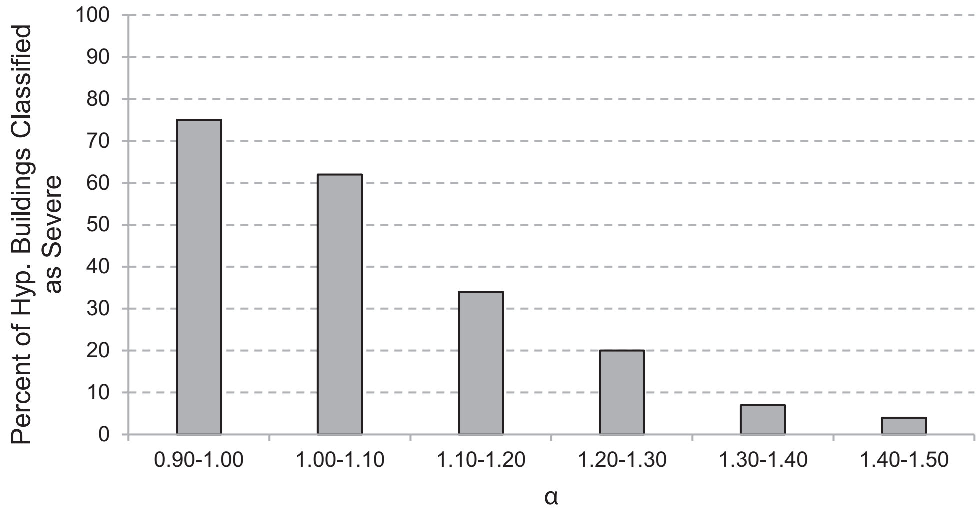


Figure 4.7: Percentage of numerical building models classified as likely to have severe damage vs α

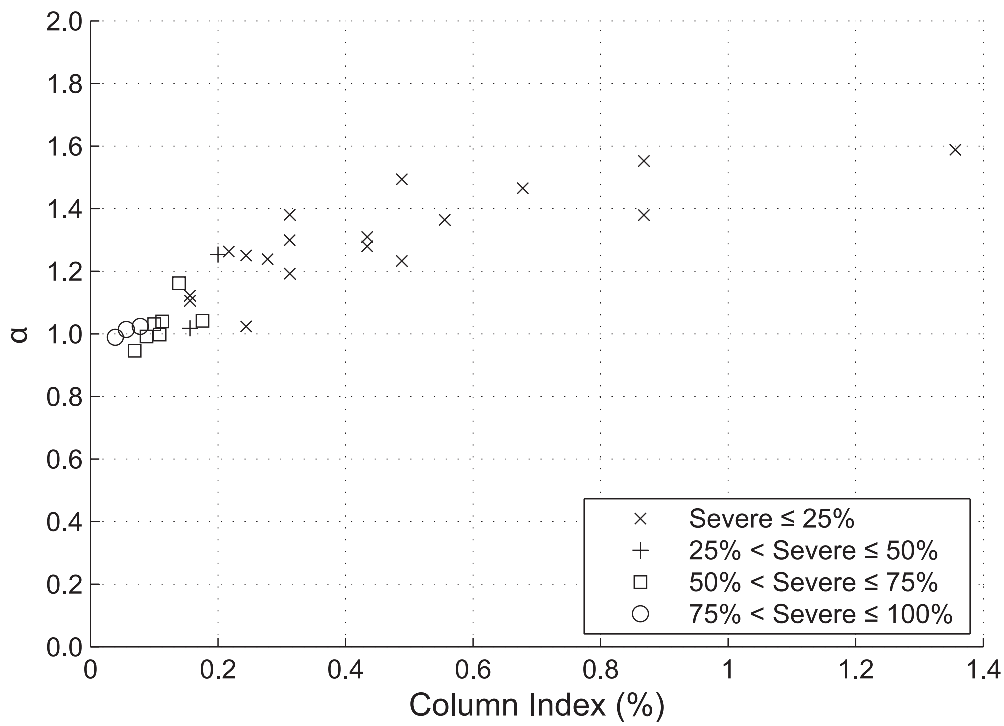


Figure 4.8: Percentage of numerical building models classified as likely to have severe damage vs α and column index

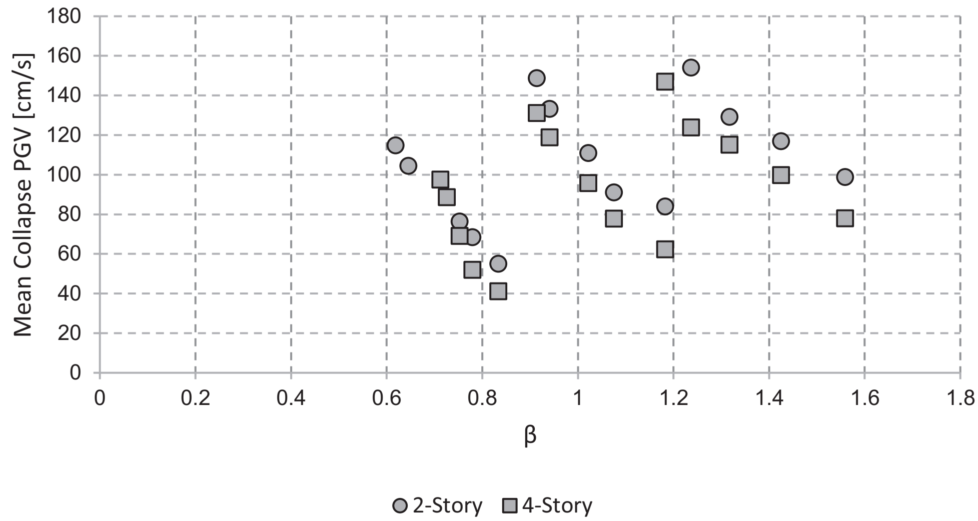


Figure 4.9: Mean Collpase PGV of the numerical building models vs β

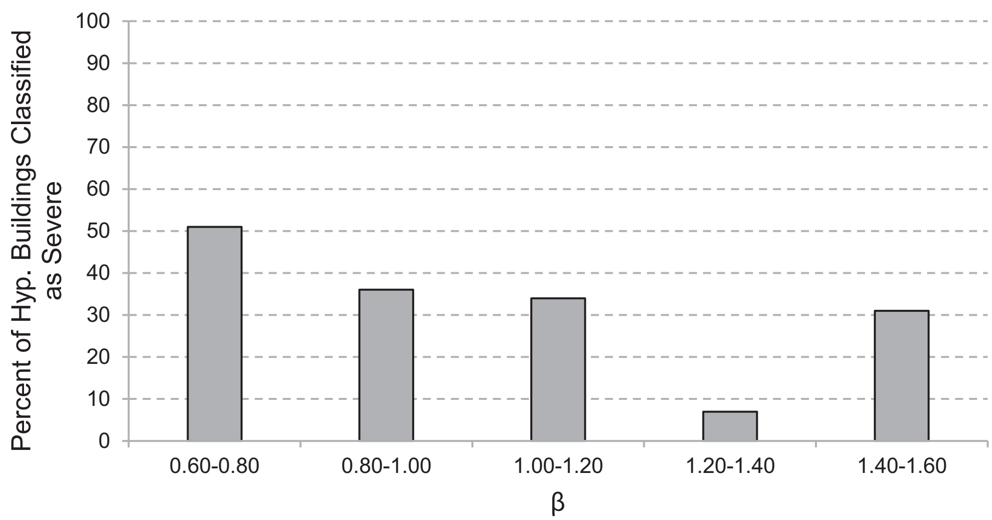


Figure 4.10: Percentage of numerical building models classified as likely to have severe damage vs β

APPENDICES

Appendix A: Alternative Building Measures

A parameter called the Mean Collapse PGA was computed for each model using the same procedure used for the Mean Collapse PGV described in Section 4.1. Mean Collapse PGA was used as an alternative measure of resistance to ground motion for a building. Figure A.1 shows a plot of Mean Collapse PGA versus column index for the numerical models representing hypothetical buildings. The Mean Collapse PGA increased as column index increased. Figure A.1 shows a good correlation between Mean Collapse PGA and column index. This was interpreted to mean that Mean Collapse PGA may be used as a measure of building resistance.

Fundamental periods were used as an alternative collapse indicator for the hypothetical frames. Frame periods were divided by the number of stories to compare the two- and four-story models. The Mean Collapse PGV versus period is plotted in Figure A.2. The Mean Collapse PGV decreased as period increased. Figure A.2 shows a good correlation between Mean Collapse PGV and fundamental period. This suggested that the fundamental period may be used as an indicator of vulnerability.

The use of maximum column axial load ratio as an alternative collapse indicator was also studied. Figure A.3 shows a plot of Mean Collapse PGV versus axial load ratio. The Mean Collapse PGV decreased as the axial load ratio increased. Figure A.3 shows a good correlation between Mean Collapse PGV and axial load ratio. This suggested that the axial load ratio may be used as an indicator of vulnerability.

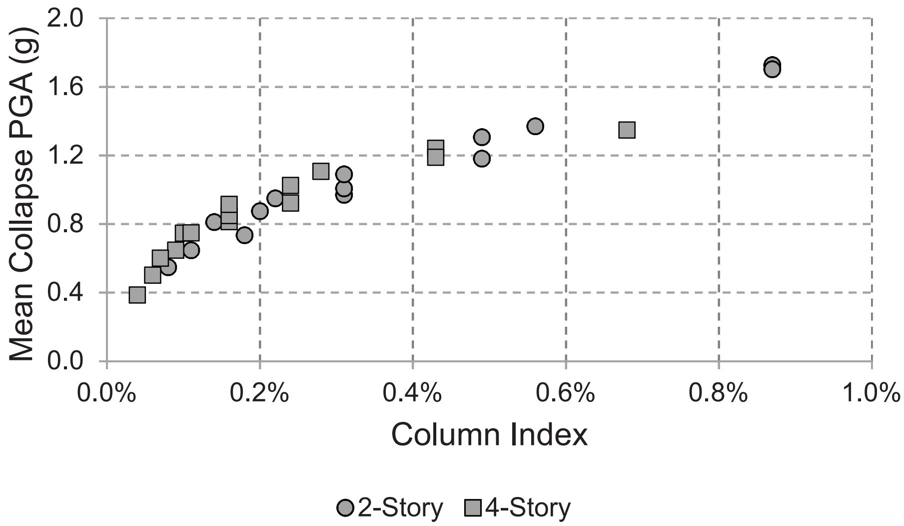


Figure A.1: Mean Collapse PGA vs column index

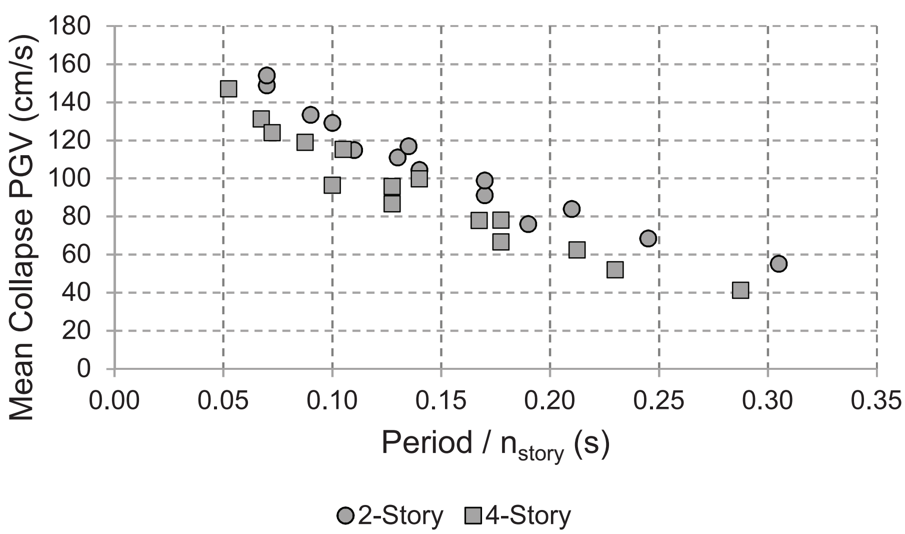


Figure A.2: Mean Collapse PGV vs fundamental period

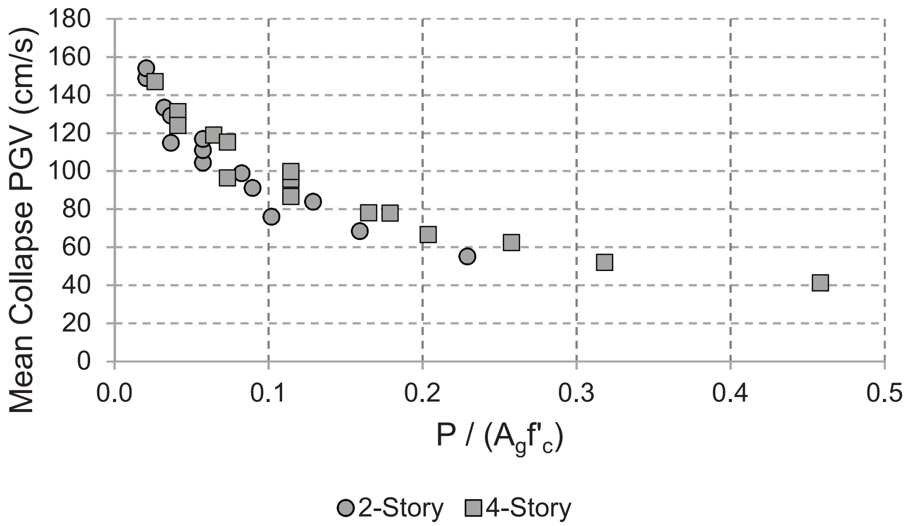


Figure A.3: Mean Collapse PGV vs axial load ratio

Appendix B: Flexural Properties for the Numerical Models

Table: B.1: Moment-rotation properties for S2-0

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	18	8750	324	2200	2640	2640	0.06	10	0	12	0.9
Columns	1	18	8750	324	2300	2760	2760	0.05	10	0	24	1.8
Interior	2	18	8750	324	2300	2760	2760	0.06	10	0	24	1.8
Columns	1	18	8750	324	2500	3000	3000	0.05	10	0	48	3.7

Table: B.2: Moment-rotation properties for S2-1

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ $(\%)$
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	18	8750	324	2300	2760	2760	0.06	10	0	19	1.4
Columns	1	18	8750	324	2400	2880	2880	0.05	10	0	37	2.9
Interior	2	18	8750	324	2400	2880	2880	0.06	10	0	37	2.9
Columns	1	18	8750	324	2800	3360	3360	0.05	10	0	74	5.7

Table: B.3: Moment-rotation properties for S2-2

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	18	8750	324	2700	3240	3240	0.06	10	0	33	2.5
Columns	1	18	8750	324	2800	3360	3360	0.05	10	0	66	5.1
Interior	2	18	8750	324	2800	3360	3360	0.06	10	0	66	5.1
Columns	1	18	8750	324	3100	3720	3720	0.05	10	0	132	10.2

Table: B.4: Moment-rotation properties for S2-3

Member	Story	Col. Size Sq. (*in*)	I_g (in^4)	A_g (in^2)	M_y (*kip-in*)	M_p (*kip-in*)	M_{res} (*kip-in*)	θ_p (*rad*)	θ_{pc} (*rad*)	λ	P_{grav} (*kip*)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	18	8750	324	2750	3300	3300	0.06	10	0	52	4.0
Columns	1	18	8750	324	2900	3480	3480	0.05	10	0	103	8.0
Interior	2	18	8750	324	2900	3480	3480	0.06	10	0	103	8.0
Columns	1	18	8750	324	3200	3840	3840	0.05	10	0	206	15.9

Table: B.5: Moment-rotation properties for S2-4

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	18	8750	324	2800	3360	3360	0.06	10	0	74	5.7
Columns	1	18	8750	324	3100	3720	3720	0.05	10	0	149	11.5
Interior	2	18	8750	324	3100	3720	3720	0.06	10	0	149	11.5
Columns	1	18	8750	324	3400	4080	4080	0.05	10	0	297	22.9

Table: B.6: Moment-rotation properties for S2-5

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ $(\%)$
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	24	27650	576	3300	3960	3960	0.06	10	0	12	0.5
Columns	1	24	27650	576	3400	4080	4080	0.05	10	0	24	1.0
Interior	2	24	27650	576	3400	4080	4080	0.06	10	0	24	1.0
Columns	1	24	27650	576	3600	4320	4320	0.05	10	0	48	2.1

Table: B.7: Moment-rotation properties for S2-6

Member	Story	Col. Size Sq. (*in*)	I_g (in^4)	A_g (in^2)	M_y (*kip-in*)	M_p (*kip-in*)	M_{res} (*kip-in*)	θ_p (*rad*)	θ_{pc} (*rad*)	λ	P_{grav} (*kip*)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	24	27650	576	3300	3960	3960	0.06	10	0	19	0.8
Columns	1	24	27650	576	3500	4200	4200	0.05	10	0	37	1.6
Interior	2	24	27650	576	3500	4200	4200	0.06	10	0	37	1.6
Columns	1	24	27650	576	3800	4560	4560	0.05	10	0	74	3.2

Table: B.8: Moment-rotation properties for S2-7

Member	Story	Col. Size Sq. (*in*)	I_g (in^4)	A_g (in^2)	M_y (*kip-in*)	M_p (*kip-in*)	M_{res} (*kip-in*)	θ_p (*rad*)	θ_{pc} (*rad*)	λ	P_{grav} (*kip*)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	24	27650	576	3400	4080	4080	0.06	10	0	33	1.4
Columns	1	24	27650	576	3800	4560	4560	0.05	10	0	66	2.9
Interior	2	24	27650	576	3800	4560	4560	0.06	10	0	66	2.9
Columns	1	24	27650	576	4250	5100	5100	0.05	10	0	132	5.7

Table: B.9: Moment-rotation properties for S2-8

Member	Story	Col. Size Sq. (*in*)	I_g (in^4)	A_g (in^2)	M_y (*kip-in*)	M_p (*kip-in*)	M_{res} (*kip-in*)	θ_p (*rad*)	θ_{pc} (*rad*)	λ	P_{grav} (*kip*)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	24	27650	576	3600	4320	4320	0.06	10	0	52	2.2
Columns	1	24	27650	576	4000	4800	4800	0.05	10	0	103	4.5
Interior	2	24	27650	576	4000	4800	4800	0.06	10	0	103	4.5
Columns	1	24	27650	576	4800	5760	5760	0.05	10	0	206	9.0

Table: B.10: Moment-rotation properties for S2-9

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	24	27650	576	3800	4560	4560	0.06	10	0	74	3.2
Columns	1	24	27650	576	4400	5280	5280	0.05	10	0	149	6.4
Interior	2	24	27650	576	4400	5280	5280	0.06	10	0	149	6.4
Columns	1	24	27650	576	5500	6600	6600	0.05	10	0	297	12.9

Table: B.11: Moment-rotation properties for S2-10

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	30	67500	900	4300	5160	5160	0.06	10	0	12	0.3
Columns	1	30	67500	900	4400	5280	5280	0.05	10	0	24	0.7
Interior	2	30	67500	900	4400	5280	5280	0.06	10	0	24	0.7
Columns	1	30	67500	900	4700	5640	5640	0.05	10	0	48	1.3

Table: B.12: Moment-rotation properties for S2-11

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y (kip-in)	M_p (kip-in)	M_{res} (kip-in)	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f_c' A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	30	67500	900	4300	5160	5160	0.06	10	0	19	0.5
Columns	1	30	67500	900	4600	5520	5520	0.05	10	0	37	1.0
Interior	2	30	67500	900	4600	5520	5520	0.06	10	0	37	1.0
Columns	1	30	67500	900	5000	6000	6000	0.05	10	0	74	2.1

Table: B.13: Moment-rotation properties for S2-12

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y (kip-in)	M_p (kip-in)	M_{res} (kip-in)	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	30	67500	900	4400	5280	5280	0.06	10	0	33	0.9
Columns	1	30	67500	900	4900	5880	5880	0.05	10	0	66	1.8
Interior	2	30	67500	900	4900	5880	5880	0.06	10	0	66	1.8
Columns	1	30	67500	900	5600	6720	6720	0.05	10	0	132	3.7

Table: B.14: Moment-rotation properties for S2-13

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y (kip-in)	M_p (kip-in)	M_{res} (kip-in)	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	30	67500	900	4700	5640	5640	0.06	10	0	52	1.4
Columns	1	30	67500	900	5300	6360	6360	0.05	10	0	103	2.9
Interior	2	30	67500	900	5300	6360	6360	0.06	10	0	103	2.9
Columns	1	30	67500	900	6400	7680	7680	0.05	10	0	206	5.7

Table: B.15: Moment-rotation properties for S2-14

Member	Story	Col. Size Sq. (*in*)	I_g (in^4)	A_g (in^2)	M_y (*kip-in*)	M_p (*kip-in*)	M_{res} (*kip-in*)	θ_p (*rad*)	θ_{pc} (*rad*)	λ	P_{grav} (*kip*)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior	2	30	67500	900	5000	6000	6000	0.06	10	0	74	2.1
Columns	1	30	67500	900	5800	6960	6960	0.05	10	0	149	4.1
Interior	2	30	67500	900	5800	6960	6960	0.06	10	0	149	4.1
Columns	1	30	67500	900	7300	8760	8760	0.05	10	0	297	8.3

Table: B.16: Moment-rotation properties for S4-0

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	18	8750	324	2600	3120	3120	0.064	10	0	12	0.9
	3	18	8750	324	2650	3180	3180	0.06	10	0	24	1.8
	2	18	8750	324	2700	3240	3240	0.06	10	0	36	2.8
	1	18	8750	324	2750	3300	3300	0.05	10	0	48	3.7
Interior Columns	4	18	8750	324	2650	3180	3180	0.06	10	0	24	1.8
	3	18	8750	324	2750	3300	3300	0.06	10	0	48	3.7
	2	18	8750	324	2900	3480	3480	0.06	10	0	71	5.5
	1	18	8750	324	3000	3600	3600	0.05	10	0	95	7.3

Table: B.17: Moment-rotation properties for S4-1

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	18	8750	324	2600	3120	3120	0.064	10	0	19	1.4
	3	18	8750	324	2700	3240	3240	0.06	10	0	37	2.9
	2	18	8750	324	2800	3360	3360	0.06	10	0	56	4.3
	1	18	8750	324	2900	3480	3480	0.05	10	0	74	5.7
Interior Columns	4	18	8750	324	2700	3240	3240	0.06	10	0	37	2.9
	3	18	8750	324	2900	3480	3480	0.06	10	0	74	5.7
	2	18	8750	324	3000	3600	3600	0.06	10	0	111	8.6
	1	18	8750	324	3100	3720	3720	0.05	10	0	149	11.5

Table: B.18: Moment-rotation properties for S4-2

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f_c' A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	18	8750	324	2700	3240	3240	0.064	10	0	33	2.5
	3	18	8750	324	2800	3360	3360	0.06	10	0	66	5.1
	2	18	8750	324	3000	3600	3600	0.06	10	0	99	7.6
	1	18	8750	324	3100	3720	3720	0.05	10	0	132	10.2
Interior Columns	4	18	8750	324	2800	3360	3360	0.06	10	0	66	5.1
	3	18	8750	324	3100	3720	3720	0.06	10	0	132	10.2
	2	18	8750	324	3300	3960	3960	0.06	10	0	198	15.3
	1	18	8750	324	3500	4200	4200	0.05	10	0	264	20.4

Table: B.19: Moment-rotation properties for S4-3

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	18	8750	324	2750	3300	3300	0.064	10	0	52	4.0
	3	18	8750	324	2900	3480	3480	0.06	10	0	103	8.0
	2	18	8750	324	3100	3720	3720	0.06	10	0	155	11.9
	1	18	8750	324	3200	3840	3840	0.05	10	0	206	15.9
Interior Columns	4	18	8750	324	2900	3480	3480	0.06	10	0	103	8.0
	3	18	8750	324	3200	3840	3840	0.06	10	0	206	15.9
	2	18	8750	324	3500	4200	4200	0.06	10	0	309	23.9
	1	18	8750	324	4000	4800	4800	0.05	10	0	413	31.8

Table: B.20: Moment-rotation properties for S4-4

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y (kip-in)	M_p (kip-in)	M_{res} (kip-in)	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	18	8750	324	2800	3360	3360	0.064	10	0	74	5.7
	3	18	8750	324	3100	3720	3720	0.06	10	0	149	11.5
	2	18	8750	324	3300	3960	3960	0.06	10	0	223	17.2
	1	18	8750	324	3400	4080	4080	0.05	10	0	297	22.9
Interior Columns	4	18	8750	324	3100	3720	3720	0.06	10	0	149	11.5
	3	18	8750	324	3400	4080	4080	0.06	10	0	297	22.9
	2	18	8750	324	4000	4800	4800	0.06	10	0	446	34.4
	1	18	8750	324	3500	4200	4200	0.05	10	0	594	45.8

Table: B.21: Moment-rotation properties for S4-5

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	24	27650	576	3300	3960	3960	0.064	10	0	12	0.5
	3	24	27650	576	3400	4080	4080	0.06	10	0	24	1.0
	2	24	27650	576	3500	4200	4200	0.06	10	0	36	1.5
	1	24	27650	576	3600	4320	4320	0.05	10	0	48	2.1
Interior Columns	4	24	27650	576	3400	4080	4080	0.06	10	0	24	1.0
	3	24	27650	576	3600	4320	4320	0.06	10	0	48	2.1
	2	24	27650	576	3700	4440	4440	0.06	10	0	71	3.1
	1	24	27650	576	3900	4680	4680	0.05	10	0	95	4.1

Table: B.22: Moment-rotation properties for S4-6

Member	Story	Col. Size Sq. (*in*)	I_g (in^4)	A_g (in^2)	M_y (*kip-in*)	M_p (*kip-in*)	M_{res} (*kip-in*)	θ_p (*rad*)	θ_{pc} (*rad*)	λ	P_{grav} (*kip*)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	24	27650	576	3300	3960	3960	0.064	10	0	19	0.8
	3	24	27650	576	3500	4200	4200	0.06	10	0	37	1.6
	2	24	27650	576	3600	4320	4320	0.06	10	0	56	2.4
	1	24	27650	576	3800	4560	4560	0.05	10	0	74	3.2
Interior Columns	4	24	27650	576	3500	4200	4200	0.06	10	0	37	1.6
	3	24	27650	576	3800	4560	4560	0.06	10	0	74	3.2
	2	24	27650	576	4100	4920	4920	0.06	10	0	111	4.8
	1	24	27650	576	4400	5280	5280	0.05	10	0	149	6.4

Table: B.23: Moment-rotation properties for S4-7

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	24	27650	576	3400	4080	4080	0.064	10	0	33	1.4
	3	24	27650	576	3800	4560	4560	0.06	10	0	66	2.9
	2	24	27650	576	4000	4800	4800	0.06	10	0	99	4.3
	1	24	27650	576	4250	5100	5100	0.05	10	0	132	5.7
Interior Columns	4	24	27650	576	3800	4560	4560	0.06	10	0	66	2.9
	3	24	27650	576	4250	5100	5100	0.06	10	0	132	5.7
	2	24	27650	576	4800	5760	5760	0.06	10	0	198	8.6
	1	24	27650	576	5250	6300	6300	0.05	10	0	264	11.5

Table: B.24: Moment-rotation properties for S4-8

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f_c' A_g}$ $(\%)$
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	24	27650	576	3600	4320	4320	0.064	10	0	52	2.2
	3	24	27650	576	4000	4800	4800	0.06	10	0	103	4.5
	2	24	27650	576	4400	5280	5280	0.06	10	0	155	6.7
	1	24	27650	576	4800	5760	5760	0.05	10	0	206	9.0
Interior Columns	4	24	27650	576	4000	4800	4800	0.06	10	0	103	4.5
	3	24	27650	576	4800	5760	5760	0.06	10	0	206	9.0
	2	24	27650	576	5600	6720	6720	0.06	10	0	309	13.4
	1	24	27650	576	6300	7560	7560	0.05	10	0	413	17.9

Table: B.25: Moment-rotation properties for S4-9

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	24	27650	576	3800	4560	4560	0.064	10	0	74	3.2
	3	24	27650	576	4400	5280	5280	0.06	10	0	149	6.4
	2	24	27650	576	5000	6000	6000	0.06	10	0	223	9.7
	1	24	27650	576	5500	6600	6600	0.05	10	0	297	12.9
Interior Columns	4	24	27650	576	4400	5280	5280	0.06	10	0	149	6.4
	3	24	27650	576	5500	6600	6600	0.06	10	0	297	12.9
	2	24	27650	576	6500	7800	7800	0.06	10	0	446	19.3
	1	24	27650	576	7300	8760	8760	0.05	10	0	594	25.8

Table: B.26: Moment-rotation properties for S4-10

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y (kip-in)	M_p (kip-in)	M_{res} (kip-in)	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	30	67500	900	4300	5160	5160	0.064	10	0	12	0.3
	3	30	67500	900	4400	5280	5280	0.06	10	0	24	0.7
	2	30	67500	900	4500	5400	5400	0.06	10	0	36	1.0
	1	30	67500	900	4700	5640	5640	0.05	10	0	48	1.3
Interior Columns	4	30	67500	900	4400	5280	5280	0.06	10	0	24	0.7
	3	30	67500	900	4700	5640	5640	0.06	10	0	48	1.3
	2	30	67500	900	5000	6000	6000	0.06	10	0	71	2.0
	1	30	67500	900	5200	6240	6240	0.05	10	0	95	2.6

Table: B.27: Moment-rotation properties for S4-11

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ $(\%)$
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	30	67500	900	4300	5160	5160	0.064	10	0	19	0.5
	3	30	67500	900	4600	5520	5520	0.06	10	0	37	1.0
	2	30	67500	900	5800	6960	6960	0.06	10	0	56	1.5
	1	30	67500	900	5000	6000	6000	0.05	10	0	74	2.1
Interior Columns	4	30	67500	900	4600	5520	5520	0.06	10	0	37	1.0
	3	30	67500	900	5000	6000	6000	0.06	10	0	74	2.1
	2	30	67500	900	5400	6480	6480	0.06	10	0	111	3.1
	1	30	67500	900	5800	6960	6960	0.05	10	0	149	4.1

Table: B.28: Moment-rotation properties for S4-12

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	30	67500	900	4400	5280	5280	0.064	10	0	33	0.9
	3	30	67500	900	4900	5880	5880	0.06	10	0	66	1.8
	2	30	67500	900	5200	6240	6240	0.06	10	0	99	2.8
	1	30	67500	900	5600	6720	6720	0.05	10	0	132	3.7
Interior Columns	4	30	67500	900	4900	5880	5880	0.06	10	0	66	1.8
	3	30	67500	900	5600	6720	6720	0.06	10	0	132	3.7
	2	30	67500	900	6300	7560	7560	0.06	10	0	198	5.5
	1	30	67500	900	7000	8400	8400	0.05	10	0	264	7.3

Table: B.29: Moment-rotation properties for S4-13

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y (kip-in)	M_p (kip-in)	M_{res} (kip-in)	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ (%)
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	30	67500	900	4700	5640	5640	0.064	10	0	52	1.4
	3	30	67500	900	5300	6360	6360	0.06	10	0	103	2.9
	2	30	67500	900	5900	7080	7080	0.06	10	0	155	4.3
	1	30	67500	900	6400	7680	7680	0.05	10	0	206	5.7
Interior Columns	4	30	67500	900	5300	6360	6360	0.06	10	0	103	2.9
	3	30	67500	900	6400	7680	7680	0.06	10	0	206	5.7
	2	30	67500	900	7500	9000	9000	0.06	10	0	309	8.6
	1	30	67500	900	8400	10080	10080	0.05	10	0	413	11.5

Table: B.30: Moment-rotation properties for S4-14

Member	Story	Col. Size Sq. (in)	I_g (in^4)	A_g (in^2)	M_y $(kip\text{-}in)$	M_p $(kip\text{-}in)$	M_{res} $(kip\text{-}in)$	θ_p (rad)	θ_{pc} (rad)	λ	P_{grav} (kip)	$\frac{P_{grav}}{f'_c A_g}$ $(\%)$
Beams +	All	-	32900	504	3550	4260	426	0.05	0.08	64	0	-
Beams -		-	32900	504	5750	6900	690	0.04	0.08	64	0	-
Exterior Columns	4	30	67500	900	5000	6000	6000	0.064	10	0	74	2.1
	3	30	67500	900	5800	6960	6960	0.06	10	0	149	4.1
	2	30	67500	900	6600	7920	7920	0.06	10	0	223	6.2
	1	30	67500	900	7300	8760	8760	0.05	10	0	297	8.3
Interior Columns	4	30	67500	900	5800	6960	6960	0.06	10	0	149	4.1
	3	30	67500	900	7300	8760	8760	0.06	10	0	297	8.3
	2	30	67500	900	8800	10560	10560	0.06	10	0	446	12.4
	1	30	67500	900	10100	12120	12120	0.05	10	0	594	16.5

Appendix C: Sample Numerical Model Files

Listing C.1: Code for the S2-0 Model

```
####################################################################
######################## DEFINE NODES ##############################
####################################################################
## S2-0 Shear-Axial

 # define structure-geometry parameters
  set Nstories 2; # number of stories
  set Nbays 4; # number of frame bays (excludes bay for P-delta column)
  set Wbay1       [expr 12.0*12.0]; # bay width in inches
  set Wbay2       [expr 12.0*12.0]; # bay width in inches
  set HStory1     [expr 12.0*12.0]; # 1st story height in inches
  set HStoryTyp   [expr 12.0*12.0]; # story height of other stories in inches
  set HBuilding   [expr $HStory1 + ($Nstories-1)*$HStoryTyp] ; # height of building

 # calculate locations of beam/column joints:
  set Pier1  0.0;   # leftmost column line
  set Pier2  [expr $Pier1 + $Wbay1];
  set Pier3  [expr $Pier1 + $Wbay1+($Nbays-3)*$Wbay2];
  set Pier4  [expr $Pier1 + $Wbay1+($Nbays-2)*$Wbay2];
  set Pier5  [expr $Pier1 + $Wbay1+($Nbays-1)*$Wbay2];

  set Floor1 0.0;   # ground floor
  set Floor2 [expr $Floor1 + $HStory1];
  set Floor3 [expr $Floor2 + ($Nstories-1)*$HStoryTyp];

# calculate joint offset distance for beam plastic hinges

  set phlat23     [expr 0.0]; # lateral dist from beam-col joint to loc of hinge (beams only)
  set phlatcols1  [expr 28.0/4];  # lateral dist from beam-col joint to loc of hinge (beams only)
  set phlatbeams1 [expr 18.0/4] ;
  set phlatbeams2 [expr 18.0/4] ;

  # calculate nodal masses -- lump floor masses at frame nodes

  set g 386.4; # acceleration due to gravity
  set deadWeight [expr 165./144./1000.] ; # 165 psf

  set load_I [expr $deadWeight*$Wbay1**2]
  set load_E [expr $load_I/2.]
  set mNode [expr $load_E/$g]

  set P_1i  [expr 2.*$load_I]
  set P_2i  [expr 1.*$load_I]

  set P_1e  [expr 2.*$load_E]
  set P_2e  [expr 1.*$load_E]

  set Dload [expr $deadWeight*$Wbay1]

  set T1_damp 0.22;
  set T3_damp 0.08;

  # Calculation of Total Building Weight

  #Define Nodal Mass Values

  set NodalMass2 $mNode;
  set Negligible 1e-9; # a very small number to avoid problems with zero

# define nodes and assign masses to beam-column intersections of frame
  # command:  node nodeID xcoord ycoord -mass mass_dof1 mass_dof2 mass_dof3
  # nodeID convention:  "xy" where x = Pier # and y = Floor #
```

```
  node 11 $Pier1 $Floor1 ;
  node 21 $Pier2 $Floor1 ;
  node 31 $Pier3 $Floor1 ;
  node 41 $Pier4 $Floor1 ;
  node 51 $Pier5 $Floor1 ;

 # define extra nodes for plastic hinge rotational springs
  # nodeID convention:  "xya" where x = Pier #, y = Floor #, a = location relative to beam-column joint
  # "a" convention: 2 = left; 3 = right;
  # "a" convention: 6 = below; 7 = above;

  # column hinges at bottom of Story 1 (base)
  node 117 $Pier1 $Floor1 ;
  node 217 $Pier2 $Floor1 ;
  node 317 $Pier3 $Floor1 ;
  node 417 $Pier4 $Floor1 ;
  node 517 $Pier5 $Floor1 ;

  # column hinges at top of Story 1
  node 126 $Pier1 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible ;
  node 226 $Pier2 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible;
  node 326 $Pier3 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible;
  node 426 $Pier4 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible;
  node 526 $Pier5 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible;

  # column hinges at bottom of Story 2
  node 127 $Pier1 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
  node 227 $Pier2 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
  node 327 $Pier3 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
  node 427 $Pier4 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
  node 527 $Pier5 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;

  # column hinges at top of Story 2
  node 136 $Pier1 [expr $Floor3-$phlatcols1-$phlat23]
  node 236 $Pier2 [expr $Floor3-$phlatcols1-$phlat23]
  node 336 $Pier3 [expr $Floor3-$phlatcols1-$phlat23]
  node 436 $Pier4 [expr $Floor3-$phlatcols1-$phlat23]
  node 536 $Pier5 [expr $Floor3-$phlatcols1-$phlat23]

###################################################################
## Define Rigid Offsets for joints
###################################################################

  # column hinges at top of Story 1
  node 10126 $Pier1 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;
  node 10226 $Pier2 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;
  node 10326 $Pier3 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;
  node 10426 $Pier4 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;
  node 10526 $Pier5 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;

  # column hinges at bottom of Story 2
  node 10127 $Pier1 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;
```

```
node 10227 $Pier2 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10327 $Pier3 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10427 $Pier4 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10527 $Pier5 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;

# column hinges at top of Story 2
node 10136 $Pier1 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10236 $Pier2 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10336 $Pier3 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10436 $Pier4 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10536 $Pier5 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;

# column hinges at bottom of Story 3
node 10137 $Pier1 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10237 $Pier2 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10337 $Pier3 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10437 $Pier4 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10537 $Pier5 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;

# beam offset at Floor 2
node 9122 [expr $Pier1 - $phlatbeams2] $Floor2 -mass $Negligible $Negligible $Negligible;
node 9123 [expr $Pier1 + $phlatbeams2] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9222 [expr $Pier2 - $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9223 [expr $Pier2 + $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9322 [expr $Pier3 - $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9323 [expr $Pier3 + $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9422 [expr $Pier4 - $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9423 [expr $Pier4 + $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9522 [expr $Pier5 - $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9523 [expr $Pier5 + $phlatbeams1] $Floor2 -mass $Negligible $Negligible $Negligible;

# beam offset at Floor 3
node 9132 [expr $Pier1 - $phlatbeams2] $Floor3 -mass $Negligible $Negligible $Negligible;
node 9133 [expr $Pier1 + $phlatbeams2] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9232 [expr $Pier2 - $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9233 [expr $Pier2 + $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9332 [expr $Pier3 - $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
```

```
  node 9333 [expr $Pier3 + $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
  node 9432 [expr $Pier4 - $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
  node 9433 [expr $Pier4 + $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
  node 9532 [expr $Pier5 - $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
  node 9533 [expr $Pier5 + $phlatbeams1] $Floor3 -mass $Negligible $Negligible $Negligible;

################################################################
################################################################

  # beam hinges at Floor 2
  node 123 [expr $Pier1 + $phlatbeams2 + $phlat23] $Floor2 -mass $Negligible $Negligible $Negligible;
  node 222 [expr $Pier2 - $phlatbeams1 + $phlat23] $Floor2 -mass $Negligible $Negligible $Negligible;
  node 223 [expr $Pier2 + $phlatbeams1 + $phlat23] $Floor2 -mass $Negligible $Negligible $Negligible;
  node 322 [expr $Pier3 - $phlatbeams1 + $phlat23] $Floor2 -mass $Negligible $Negligible $Negligible;
  node 323 [expr $Pier3 + $phlatbeams1 + $phlat23] $Floor2 -mass $Negligible $Negligible $Negligible;
  node 422 [expr $Pier4 - $phlatbeams1 + $phlat23] $Floor2 -mass $Negligible $Negligible $Negligible;
  node 423 [expr $Pier4 + $phlatbeams1 + $phlat23] $Floor2 -mass $Negligible $Negligible $Negligible;
  node 522 [expr $Pier5 - $phlatbeams1 + $phlat23] $Floor2 -mass $Negligible $Negligible $Negligible;

  # beam hinges at Floor 3
  node 133 [expr $Pier1 + $phlatbeams2 + $phlat23] $Floor3 -mass $Negligible $Negligible $Negligible;
  node 232 [expr $Pier2 - $phlatbeams1 + $phlat23] $Floor3 -mass $Negligible $Negligible $Negligible;
  node 233 [expr $Pier2 + $phlatbeams1 + $phlat23] $Floor3 -mass $Negligible $Negligible $Negligible;
  node 332 [expr $Pier3 - $phlatbeams1 + $phlat23] $Floor3 -mass $Negligible $Negligible $Negligible;
  node 333 [expr $Pier3 + $phlatbeams1 + $phlat23] $Floor3 -mass $Negligible $Negligible $Negligible;
  node 432 [expr $Pier4 - $phlatbeams1 + $phlat23] $Floor3 -mass $Negligible $Negligible $Negligible;
  node 433 [expr $Pier4 + $phlatbeams1 + $phlat23] $Floor3 -mass $Negligible $Negligible $Negligible;
  node 532 [expr $Pier5 - $phlatbeams1 + $phlat23] $Floor3 -mass $Negligible $Negligible $Negligible;

  uniaxialMaterial Elastic 666 [expr 50.*4500000.]

  element Joint2D 7777712 10126 9123 10127 9122  12 666 1
  element Joint2D 7777713 10136 9133 10137 9132  13 666 1

  element Joint2D 7777722 10226 9223 10227 9222 22 666 1
  element Joint2D 7777723 10236 9233 10237 9232 23 666 1

  element Joint2D 7777732 10326 9323 10327 9322 32 666 1
  element Joint2D 7777733 10336 9333 10337 9332 33 666 1

  element Joint2D 7777742 10426 9423 10427 9422 42 666 1
  element Joint2D 7777743 10436 9433 10437 9432 43 666 1

  element Joint2D 7777752 10526 9523 10527 9522 52 666 1
  element Joint2D 7777753 10536 9533 10537 9532 53 666 1


# assign boundary conditions
  # command:  fix nodeID dxFixity dyFixity rzFixity
```

```
  # fixity values: 1 = constrained; 0 = unconstrained
  # fix the base of the building; pin P-delta column at base

  fix 11 1 1 1;
  fix 21 1 1 1;
  fix 31 1 1 1;
  fix 41 1 1 1;
  fix 51 1 1 1;

#################################################################
# Define Section Properties and Elements
#################################################################
# define material properties
  set Ec 3600.; # concrete Young's modulus

# set up geometric transformations of element
  set PDeltaTransf 10;
  geomTransf PDelta $PDeltaTransf ; # PDelta transformation

  set LinearTransf  20;
  geomTransf Linear  $LinearTransf; # PDelta transformation

#################################################################
#################################################################
# Column Elements Properties
#################################################################
#################################################################

#################################################################
# General Properties of Column Cross Sections
#################################################################

  set Ec 3600.;     # concrete Young's modulus

# define column section 20"x20" for Storey 1,2 & 3
# Interior Columns
  set Acol_123  324.;   # cross-sectional area
  set modcolscrack1 0.3  ;  #if 1 cracking of elastic section of beam not taken into account - if 0.3 taken into account
  set Icol_123  [expr $modcolscrack1* 8748.]; # moment of inertia

#Exterior Columns
  set Acol_1231  324.;    # cross-sectional area
  set modcolscrack1 0.3  ;  #if 1 cracking of elastic section of beam not taken into account - if 0.3 taken into account
  set Icol_1231  [expr $modcolscrack1* 8748.];  # moment of inertia

  set w1 18.
  set h1 18.

  set w2 18.
  set h2 18.

  set rho1int 0.00102 ;
  set Fsw1int 17.     ;
  set rho2int 0.00102 ;
  set Fsw2int 17.     ;

  set rho1ext 0.00102 ;
  set Fsw1ext 17.     ;
  set rho2ext 0.00102 ;
  set Fsw2ext 17.     ;

  # determine stiffness modifications to equate the stiffness of the spring-elastic element-spring subassembly to the stiffness of the actual frame member
  # Reference:  Ibarra, L. F., and Krawinkler, H. (2005). "Global collapse of frame structures under seismic excitations," Technical Report 152,
  #             The John A. Blume Earthquake Engineering Research Center, Department of Civil Engineering, Stanford University, Stanford, CA.
  # calculate modified section properties to account for spring stiffness being in series with the elastic element stiffness
  set n 10.0;   # stiffness multiplier for rotational spring
  set n1 100.0 ;  # stiffness multiplier for shear and axial spring

  # calculate modified moment of inertia for elastic elements
  #Interior
```

```
  set Icol_123mod  [expr $Icol_123*($n+1.0)/$n];  # modified moment of inertia for columns in Story 1,2

  #Exterior
  set Icol_1231mod  [expr $Icol_1231*($n+1.0)/$n];  # modified moment of inertia for columns in Story 1,2

  # calculate modified rotational stiffness for plastic hinge springs
  #Interior
  set Ks_col_1123   [expr $n*6.0*$Ec*$Icol_123mod/$HStory1];    # rotational stiffness of Story 1 column springs
  set Ks_col_2123   [expr $n*6.0*$Ec*$Icol_123mod/$HStoryTyp];  # rotational stiffness of Story 2 column springs

  #Exterior
  set Ks_col_11231   [expr $n*6.0*$Ec*$Icol_1231mod/$HStory1];    # rotational stiffness of Story 1 column springs
  set Ks_col_21231   [expr $n*6.0*$Ec*$Icol_1231mod/$HStoryTyp];  # rotational stiffness of Story 2 column springs


##############################################################
# Parameters for Shear Limit State Material
##############################################################

  set s1psh 10.0
  set s2psh 20.0
  set s3psh 90.0
  set s1nsh -10.0
  set s2nsh -20.0
  set s3nsh -90.0
  set pinchXsh 0.5
  set pinchYsh 0.5
    set damage1sh 0.05
  set damage2sh 0.05
  set betash 0
  set curveTypesh 2

  set Av_123 [expr (5./6.)*$Acol_123];

  set Ksh_col_1123   [expr ($Ec/2.3)*$Av_123/$HStory1]; # Shear Stiffness G*Av/L
  set Ksh_col_2123   [expr ($Ec/2.3)*$Av_123/$HStoryTyp]; # Shear Stiffness G*Av/L

  set Ksf_1i [expr -100.] ;
  set Ksf_1e [expr -100.] ;

  set Ksf_2i [expr -100.] ;
  set Ksf_2e [expr -100.] ;

##############################################################
# Parameters for Axial Limit State Material
##############################################################

  set s1pax 10.0
  set s2pax 30.0
  set s3pax 90.0
  set s1nax -10.0
  set s2nax -30.0
  set s3nax -90.0
  set pinchXax 0.5
  set pinchYax 0.5
    set damage1ax 0.05
  set damage2ax 0.05
  set betaax 0.0
  set curveTypeax 1

  set Kax_col_1123   [expr $n1*$Ec*$Acol_123/$HStory1];   # rotational stiffness of Story 1 column springs
  set Kax_col_2123   [expr $n1*$Ec*$Acol_123/$HStoryTyp]; # rotational stiffness of Story 2 column springs

  set Kad_col_1123   [expr -0.01*$Ec*$Acol_123/$HStory1];   # rotational stiffness of Story 1 column springs
```

```
  set Kad_col_2123   [expr -0.01*$Ec*$Acol_123/$HStoryTyp]; # rotational stiffness of Story 2 column springs

# define elastic column elements using "element" command
  # command: element elasticBeamColumn $eleID $iNode $jNode $A $E $I $transfID
  # eleID convention:  "1xy" where 1 = col, x = Pier #, y = Story #
  # Columns Story 1
  element elasticBeamColumn  111  117 126 $Acol_123 $Ec  $Icol_1231mod  $PDeltaTransf;  # Pier 1
  element elasticBeamColumn  121  217 226 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf; # Pier 2
  element elasticBeamColumn  131  317 326 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf; # Pier 3
  element elasticBeamColumn  141  417 426 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf; # Pier 4
  element elasticBeamColumn  151  517 526 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf; # Pier 5

  # Columns Story 2
  element elasticBeamColumn  112  127 136 $Acol_123 $Ec  $Icol_1231mod  $PDeltaTransf;  # Pier 1
  element elasticBeamColumn  122  227 236 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf; # Pier 2
  element elasticBeamColumn  132  327 336 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf; # Pier 3
  element elasticBeamColumn  142  427 436 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf; # Pier 4
  element elasticBeamColumn  152  527 536 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf; # Pier 5

  # Soft Elastic Material Spring
  # Definition of Soft Material
  uniaxialMaterial Elastic 1 99.9

#Column Hinge Properties

# General input values for Column springs

  set LS1 0.0;      # basic strength deterioration (a very large  # = no cyclic deterioration)
  set LK1 0.0;      # unloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LA1 0.0;      # accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LD1 0.0 ;     # post-capping strength deterioration (a very large # = no deterioration)

  set LS2 0.0;      # basic strength deterioration (a very large  # = no cyclic deterioration)
  set LK2 0.0;      # unloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LA2 0.0;      # accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LD2 0.0 ;     # post-capping strength deterioration (a very large # = no deterioration)

  set cS 1.0;       # exponent for basic strength deterioration (c = 1.0 for no deterioration)
  set cK 1.0;       # exponent for unloading stiffness deterioration (c = 1.0 for no deterioration)
  set cA 1.0;       # exponent for accelerated reloading stiffness deterioration (c = 1.0 for no deterioration)
  set cD 1.0;       # exponent for post-capping strength deterioration (c = 1.0 for no deterioration)

  set th_pc1P 10.0;     # post-capping rot capacity for pos loading
  set th_pc1N 10.0;     # post-capping rot capacity for neg loading
  set th_pc2P 10.0;     # post-capping rot capacity for pos loading
    set th_pc2N 10.0;     # post-capping rot capacity for neg loading

  set ResP 1.00;      # residual strength ratio for pos loading
```

```
    set ResN 1.00;      # residual strength ratio for neg loading
    set th_uP 10.1;     # ultimate rot capacity for pos loading
    set th_uN 10.1;     # ultimate rot capacity for neg loading

    set DP 1.0;       # rate of cyclic deterioration for pos loading
    set DN 1.0;       # rate of cyclic deterioration for neg loading

    set McMy1 1.20

    set th_p1P 0.048;
    set th_p1N 0.048;
    set th_p2P 0.060;
    set th_p2N 0.060;

    set My_c1i 2500.
    set My_c2i 2300.

    set My_c1e 2300.
    set My_c2e 2200.

# define column springs
    # Spring ID: "3xya", where 3 = col spring, x = Pier #, y = Story #, a = location in story
    # "a" convention: 1 = bottom of story, 2 = top of story
    # command: rotSpring2DModIKModel id ndR ndC K McMy MyPos MyNeg LS LK LA LD cS cK cA cD th_p+ th_p- th_pc+ th_pc- Res+ Res- th_u+ th_u- D+ D-

    # col springs @ bottom of Story 1 (at base)
    rotSpring2DModIKModel 3111 11 117 $Ks_col_11231 $McMy1 [expr $My_c1e] [expr -$My_c1e] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 3211 21 217 $Ks_col_1123 $McMy1 [expr $My_c1i] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 3311 31 317 $Ks_col_1123 $McMy1 [expr $My_c1i] [expr -$My_c1i]  $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 3411 41 417 $Ks_col_1123 $McMy1 [expr $My_c1i] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 3511 51 517 $Ks_col_11231 $McMy1 [expr $My_c1e] [expr -$My_c1e] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;

#col springs @ top of Story 1 (below Floor 2)
    rotSpring2DModIKModel2 3112 10126 126 $w1 $h1 $Ks_col_11231 $McMy1 [expr $My_c1e] [expr -$My_c1e] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr $s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1ext $Fsw1ext $Ksf_1e\
    $s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123

    rotSpring2DModIKModel2 3212 10226 226 $w1 $h1 $Ks_col_1123 $McMy1 [expr $My_c1i] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr $s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1int $Fsw1int $Ksf_1i\
    $s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123
```

```
rotSpring2DModIKModel2 3312 10326 326 $w1 $h1 $Ks_col_1123 $McMy1 [expr $My_c1i ] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr $s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1int $Fsw1int $Ksf_1i\
$s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123
rotSpring2DModIKModel2 3412 10426 426 $w1 $h1 $Ks_col_1123 $McMy1 [expr $My_c1i ] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr $s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1int $Fsw1int $Ksf_1i\
$s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123
rotSpring2DModIKModel2 3512 10526 526 $w1 $h1 $Ks_col_11231 $McMy1 [expr $My_c1e] [expr -$My_c1e ] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr $s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1int $Fsw1int $Ksf_1e\
$s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123

# col springs @ bottom of Story 2 (above Floor 2)
rotSpring2DModIKModel 3121 10127 127 $Ks_col_21231 $McMy1 [expr $My_c2e] [ expr -$My_c2e ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;
rotSpring2DModIKModel 3221 10227 227 $Ks_col_2123 $McMy1 [expr $My_c2i ] [ expr -$My_c2i ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;
rotSpring2DModIKModel 3321 10327 327 $Ks_col_2123 $McMy1 [expr $My_c2i ] [ expr -$My_c2i ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;
rotSpring2DModIKModel 3421 10427 427 $Ks_col_2123 $McMy1 [expr $My_c2i ] [ expr -$My_c2i ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;
rotSpring2DModIKModel 3521 10527 527 $Ks_col_21231 $McMy1 [expr $My_c2e] [ expr -$My_c2e ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;

#col springs @ top of Story 2 (below Floor 3)
rotSpring2DModIKModel2 3122 10136 136 $w1 $h1 $Ks_col_21231 $McMy1 [expr $My_c2e ] [expr -$My_c2e ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh /$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho2ext $Fsw2ext $Ksf_2e\
$s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123
rotSpring2DModIKModel2 3222 10236 236 $w1 $h1 $Ks_col_2123 $McMy1 [expr $My_c2i ] [expr -$My_c2i ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr
```

```
$s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/
$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/
$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh
$damage1sh $damage2sh $betash $curveTypesh $rho2int $Fsw2int $Ksf_2i\
  $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr
      $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/
      $Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax
      $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123
  rotSpring2DModIKModel2 3322 10336 336 $w1 $h1 $Ks_col_2123  $McMy1   [expr $My_c2i
      ]    [expr -$My_c2i ]          $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P
      $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh
      /$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/
      $Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/
      $Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh
      $damage1sh $damage2sh $betash $curveTypesh $rho2int $Fsw2int $Ksf_2i\
  $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr
      $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/
      $Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax
      $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123;
  rotSpring2DModIKModel2 3422 10436 436 $w1 $h1 $Ks_col_2123  $McMy1   [expr $My_c2i
      ]    [expr -$My_c2i ]          $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P
      $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh
      /$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/
      $Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/
      $Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh
      $damage1sh $damage2sh $betash $curveTypesh $rho2int $Fsw2int $Ksf_2i\
  $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr
      $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/
      $Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax
      $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123;
  rotSpring2DModIKModel2 3522 10536 536 $w1 $h1 $Ks_col_21231  $McMy1   [expr $My_c2e
       ]    [expr -$My_c2e ]          $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P
      $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh
      /$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/
      $Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/
      $Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh
      $damage1sh $damage2sh $betash $curveTypesh $rho2int $Fsw2int $Ksf_2e\
  $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr
      $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/
      $Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax
      $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123

##################################################################
##################################################################
# Beam Elements Properties
##################################################################
##################################################################

##################################################################
# General Properties of Beam Cross Sections
##################################################################
  set Ec 3600.;     # concrete Young's modulus

# define beam section 18"x28" for Floor 2,3 & 4
    set modbeamscrack 0.6
  set Abeam_234  504.;    # cross-sectional area (full section properties)
  set Ibeam_234  [expr $modbeamscrack*32928.];  # moment of inertia  (full section
      properties)

# define beam section 16"x28" for Floor 5,6 & 7
# set Abeam_567  448;   # cross-sectional area (full section properties)

  set Abeam_567  504.;    # cross-sectional area (full section properties)
  set Ibeam_567  [expr $modbeamscrack*32928.];  # moment of inertia  (full section
      properties)

# determine stiffness modifications to equate the stiffness of the spring-elastic
    element-spring subassembly to the stiffness of the actual frame member
```

```
  # Reference:  Ibarra, L. F., and Krawinkler, H. (2005). "Global collapse of frame structures under seismic excitations," Technical Report 152,
  #             The John A. Blume Earthquake Engineering Research Center, Department of Civil Engineering, Stanford University, Stanford, CA.
  # calculate modified section properties to account for spring stiffness being in series with the elastic element stiffness
  set n 10.0;  # stiffness multiplier for rotational spring

  # calculate modified moment of inertia for elastic elements

  set Ibeam_234mod [expr $Ibeam_234*($n+1.0)/$n]; # modified moment of inertia for beams in Floor 2,3 & 4
  set Ibeam_567mod [expr $Ibeam_567*($n+1.0)/$n]; # modified moment of inertia for beams in Floor 5,6 & 7


  set Ks_beam_1234 [expr $n*6.0*$Ec*$Ibeam_234mod/$Wbay1];   # rotational stiffness of Floor 2,3 & 4 beam springs
  set Ks_beam_2234 [expr $n*6.0*$Ec*$Ibeam_234mod/$Wbay2];   # rotational stiffness of Floor 2,3 & 4 beam springs
  set Ks_beam_1567 [expr $n*6.0*$Ec*$Ibeam_567mod/$Wbay1];   # rotational stiffness of Floor 2,3 & 4 beam springs
  set Ks_beam_2567 [expr $n*6.0*$Ec*$Ibeam_567mod/$Wbay2];   # rotational stiffness of Floor 2,3 & 4 beam springs


  # Elastic Beam Column Elements

  # eleID convention:  "2xy" where 2 = beam, x = Bay #, y = Floor #
  # Beams Story 1
  element elasticBeamColumn  212  123 222 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
  element elasticBeamColumn  222  223 322 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
  element elasticBeamColumn  232  323 422 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
  element elasticBeamColumn  242  423 522 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;

  # Beams Story 2
  element elasticBeamColumn  213  133 232 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
  element elasticBeamColumn  223  233 332 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
  element elasticBeamColumn  233  333 432 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
  element elasticBeamColumn  243  433 532 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;

##################################################################
# Define Rotational Springs for Plastic Hinges
##################################################################

# General input values for Beam Springs

  set LS13 64.0; # basic strength deterioration (a very large # = no cyclic deterioration)
  set LK13 0.0; # unloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LA13 0.0; # accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LD13 64.0; # post-capping strength deterioration (a very large # = no deterioration)

  set LS14 64.0; # basic strength deterioration (a very large # = no cyclic deterioration)
  set LK14 0.0; #  unloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LA14 0.0; #  accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
```

```
  set LD14 64.0; # post-capping strength deterioration (a very large # = no deterioration)

  set cS 1.0; # exponent for basic strength deterioration (c = 1.0 for no deterioration)
  set cK 1.0; # exponent for unloading stiffness deterioration (c = 1.0 for no deterioration)
  set cA 1.0; # exponent for accelerated reloading stiffness deterioration (c = 1.0 for no deterioration)
  set cD 1.0; # exponent for post-capping strength deterioration (c = 1.0 for no deterioration)

  set th_pc13P 0.076; # post-capping rot capacity for pos loading
  set th_pc13N 0.076; # post-capping rot capacity for neg loading

  set th_pc14P 0.076; # post-capping rot capacity for pos loading
  set th_pc14N 0.076; # post-capping rot capacity for neg loading

  set ResP 0.10; # residual strength ratio for pos loading
  set ResN 0.10; # residual strength ratio for neg loading
  set th_uP 0.20; # ultimate rot capacity for pos loading
  set th_uN 0.20; # ultimate rot capacity for neg loading

  set DP 1.0; # rate of cyclic deterioration for pos loading
  set DN 1.0; # rate of cyclic deterioration for neg loading

  set McMy13 1.20
  set McMy14 1.20

  set th_p13P 0.049;
  set th_p13N 0.043;

  set th_p14P 0.046;
  set th_p14N 0.046;

  set My_bP 3550.
  set My_bN [expr -5750.]

#Story 1

  #beam springs at Floor 2
  rotSpring2DModIKModel 4121 9123 123 $Ks_beam_1234 $McMy13 $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4122 9222 222 $Ks_beam_1234 $McMy13 $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel 4221 9223 223 $Ks_beam_2234 $McMy13 $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4222 9322 322 $Ks_beam_2234 $McMy13 $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel 4321 9323 323 $Ks_beam_2234 $McMy13 $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4322 9422 422 $Ks_beam_2234 $McMy13 $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel 4421 9423 423 $Ks_beam_1234 $McMy13 $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4422 9522 522 $Ks_beam_1234 $McMy13 $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN $ResP $th_uN $th_uP $DN $DP;

# Story 2

  #beam springs at Floor 3
```

```
  rotSpring2DModIKModel 4131 9133 133 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4132 9232 232 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel 4231 9233 233 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4232 9332 332 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel 4331 9333 333 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4332 9432 432 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel 4431 9433 433 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4432 9532 532 $Ks_beam_1234 $McMy13  $My_bP $My_bN  $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;

############################################################################
# Gravity Loads & Gravity Analysis
############################################################################
# apply gravity loads
  #command: pattern PatternType $PatternID TimeSeriesType
  pattern Plain 1010 Constant {

  # point loads on leaning column nodes
    # command: load node Fx Fy Mz

      set P_PD1 [expr -$load_E]; # Pier 1
      set P_PD2 [expr -$load_I]; # Pier 2
      set P_PD3 [expr -$load_I]; # Pier 3
      set P_PD4 [expr -$load_I]; # Pier 4
      set P_PD5 [expr -$load_E]; # Pier 5

      load 10127 0.0 $P_PD1 0.0   ; # Pier 1
      load 10227 0.0 $P_PD2 0.0   ; # Pier 2
      load 10327 0.0 $P_PD3 0.0   ; # Pier 3
      load 10427 0.0 $P_PD4 0.0   ; # Pier 4
      load 10527 0.0 $P_PD5 0.0   ; # Pier 5


      load 10137 0.0 $P_PD1 0.0   ; # Pier 1
      load 10237 0.0 $P_PD2 0.0   ; # Pier 2
      load 10337 0.0 $P_PD3 0.0   ; # Pier 3
      load 10437 0.0 $P_PD4 0.0   ; # Pier 4
      load 10537 0.0 $P_PD5 0.0   ; # Pier 5

  }

############################################################################
# define DAMPING
############################################################################
# apply Rayleigh DAMPING from $xDamp
# D=$alphaM*M + $betaKcurr*Kcurrent + $betaKcomm*KlastCommit + $beatKinit*$Kinitial

  set xDamp 0.02; # 2% damping ratio

  set omega1 [expr 6.2832/$T1_damp]
  set omega3 [expr 6.2832/$T3_damp]

  set alpha1 [expr $xDamp*2*$omega1*$omega3/($omega1+$omega3)];
  set alpha2 [expr 2.*$xDamp/($omega1+$omega3)];
```

```
    set alphaM [expr $xDamp*2*$omega1*$omega3/($omega1+$omega3)];
    set betaKcurr 0.;
    set betaKcomm 0.;
    set betaKinit [expr 2.*$xDamp/($omega1+$omega3)];
    set betaKinit_mod [expr $betaKinit*1.1];

# define damping
# Beam Regions by Bay
    region 555 -eleRange 212 213 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
    region 556 -eleRange 222 223 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
    region 557 -eleRange 232 233 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
    region 558 -eleRange 242 243 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;

    # Column Regions by Pier
    region 560 -eleRange 111 112 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
    region 561 -eleRange 121 122 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
    region 562 -eleRange 131 132 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
    region 563 -eleRange 141 142 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
    region 564 -eleRange 151 152 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;

    region 1 -node  10126 9123 10127 9122 -rayleigh $alphaM 0.0 0.0 0.0; # assign mass proportional damping to structure (assign to nodes with mass)
    region 2 -node  10136 9133 10137 9132 -rayleigh $alphaM 0.0 0.0 0.0;

    region 8 -node  10226 9223 10227 9222 -rayleigh $alphaM 0.0 0.0 0.0;
    region 9 -node  10236 9233 10237 9232 -rayleigh $alphaM 0.0 0.0 0.0;

    region 15 -node 10326 9323 10327 9322 -rayleigh $alphaM 0.0 0.0 0.0;
    region 16 -node 10336 9333 10337 9332 -rayleigh $alphaM 0.0 0.0 0.0;

    region 21 -node 10426 9423 10427 9422 -rayleigh $alphaM 0.0 0.0 0.0;
    region 22 -node 10436 9433 10437 9432 -rayleigh $alphaM 0.0 0.0 0.0;

    region 27 -node 10526 9523 10527 9522 -rayleigh $alphaM 0.0 0.0 0.0;
    region 28 -node 10536 9533 10537 9532 -rayleigh $alphaM 0.0 0.0 0.0;

####################################################################################
####################################################################################
### DEFINE ANALYSIS OPTIONS, NEEDED LISTS OF STUFF TO RECORD, ETC.
# Define control nodes for monotonic and cyclic pushover - at top of leaning column
      set poControlNodeNum          13
      set poControlNodeNumCyclic    13
# Define a list of element numbers to record - record the columns or primary frame and leaning column - these are used for computing base shear and story shear
     set elementNumToRecordLIST { 111 121    112 122  }

# Define a list of joint numbers to record - all joints of primary frame
     set jointNumToRecordLIST {}

# Define a list of node numbers to record - top/bottom node of joint in left column of each floor, leaning column nodes, base spring nodes
     set nodeNumToRecordLIST { 126 226  10126 10226  11 12 13   31 32 33}
   set springnodeNumToRecordLIST { 116 126  216 226   316 326   }
# Define a list of hinge elements to record - these are the springs at the base of the columns (elastic foundation + column PH)
     set hingeElementsToRecordLIST  {}

# Define a list of column numbers at the base of the frame (including the leaning column); this is for base shear calculations
     set columnNumsAtBaseLIST { 111 121 131 141 151}

# Define a list of column numbers at each story (including the leaning column); this is for story shear calculations
     set columnNumsAtEachStoryLIST { { 111 121 131 141 151 }
     { 112 122 132 142 152 } }

############################### Panos ###############################

   set zerolengthelementNumToRecordLIST  { { 3112 3212 3312 3412 3512
                                            { 3122 3222 3322 3422 3522 }}
```

```
######################### End Panos #########################

# Define a list of heights of each floor (for computing story drifts)
    set floorHeightsLIST { 0 144 288}

# Define a list of the node numbers at each floor (always use node 3 of the joint
    because it is at the slab level and we measure all height to there)
    set nodeNumsAtEachFloorLIST {-1  12 13}

########################### Panos ###########################

  set nodeNums1stFloorSpringsLIST {12 22 32 42 52};
  set nodeNums2ndFloorSpringsLIST {13 23 33 43 53};

  set springnodeNums1stFloorSpringsLIST {126 226 326 426 526};
  set springnodeNums2ndFloorSpringsLIST {136 236 336 436 536};

######################### End Panos #########################

###############################################################
#### START NRS

   set columnRhoLIST { {   0.00102   0.00102   0.00102   0.00102   0.00102 }
    {   0.00102   0.00102   0.00102   0.00102   0.00102 }}

   set columnFswLIST { { 17. 17. 17. 17. 17.}
     { 17. 17. 17. 17. 17.}}

   set columnWidthLIST { { 18. 18. 18. 18. 18.}
     { 18. 18. 18. 18. 18.} }

   set columnDepthLIST { { 15.5 15.5 15.5 15.5 15.5}
     { 15.5 15.5 15.5 15.5 15.5}}

  set fpc_NRS 4000.
#### END NRS
###############################################################
```

Listing C.1: Code for the S4-0 Model

```
#################################################################
###################### DEFINE NODES #########################
#################################################################
## S4-0 Shear-Axial

 # define structure-geometry parameters
  set Nstories 4; # number of stories
  set Nbays 4;  # number of frame bays (excludes bay for P-delta column)
  set Wbay1       [expr 12.0*12.0]; # bay width in inches
  set Wbay2       [expr 12.0*12.0]; # bay width in inches
  set HStory1     [expr 12.0*12.0]; # 1st story height in inches
  set HStoryTyp   [expr 12.0*12.0]; # story height of other stories in inches
  set HBuilding   [expr $HStory1 + ($Nstories-1)*$HStoryTyp] ; # height of building

 # calculate locations of beam/column joints:
  set Pier1  0.0; # leftmost column line
  set Pier2  [expr $Pier1 + $Wbay1];
  set Pier3  [expr $Pier1 + $Wbay1+($Nbays-3)*$Wbay2];
  set Pier4  [expr $Pier1 + $Wbay1+($Nbays-2)*$Wbay2];
  set Pier5  [expr $Pier1 + $Wbay1+($Nbays-1)*$Wbay2];

  set Floor1 0.0; # ground floor
  set Floor2 [expr $Floor1 + $HStory1];
  set Floor3 [expr $Floor2 + ($Nstories-3)*$HStoryTyp];
  set Floor4 [expr $Floor2 + ($Nstories-2)*$HStoryTyp];
  set Floor5 [expr $Floor2 + ($Nstories-1)*$HStoryTyp];


# calculate joint offset distance for beam plastic hinges

  set phlat23     [expr 0.0]; # lateral dist from beam-col joint to loc of hinge (beams only)
  set phlatcols1  [expr 28.0/4]; # lateral dist from beam-col joint to loc of hinge (beams only)
  set phlatbeams1 [expr 18.0/4] ;
  set phlatbeams2 [expr 18.0/4] ;

# calculate nodal masses -- lump floor masses at frame nodes

  set g 386.4;        # acceleration due to gravity
  set deadWeight [expr 165./144./1000.] ; # 165 psf

  set load_I [expr $deadWeight*$Wbay1**2]
  set load_E [expr $load_I/2.]
  set mNode [expr $load_E/$g]

  set P_1i  [expr 4.*$load_I]
  set P_2i  [expr 3.*$load_I]
  set P_3i  [expr 2.*$load_I]
  set P_4i  [expr 1.*$load_I]

  set P_1e  [expr 4.*$load_E]
  set P_2e  [expr 3.*$load_E]
  set P_3e  [expr 2.*$load_E]
  set P_4e  [expr 1.*$load_E]

  set Dload [expr $deadWeight*$Wbay1]
  set T1_damp 0.40;
  set T3_damp 0.09;

  #Define Nodal Mass Values

  set NodalMass2 $mNode;
  set Negligible 1e-9;  # a very small number to avoid problems with zero

# define nodes and assign masses to beam-column intersections of frame
  # command:  node nodeID xcoord ycoord -mass mass_dof1 mass_dof2 mass_dof3
  # nodeID convention:  "xy" where x = Pier # and y = Floor #

```

```
 node 11 $Pier1 $Floor1 ;
 node 21 $Pier2 $Floor1 ;
 node 31 $Pier3 $Floor1 ;
 node 41 $Pier4 $Floor1 ;
 node 51 $Pier5 $Floor1 ;

# define extra nodes for plastic hinge rotational springs
 # nodeID convention: "xya" where x = Pier #, y = Floor #, a = location relative to beam-column joint
 # "a" convention: 2 = left; 3 = right;
 # "a" convention: 6 = below; 7 = above;

 # column hinges at bottom of Story 1 (base)
 node 117 $Pier1 $Floor1 ;
 node 217 $Pier2 $Floor1 ;
 node 317 $Pier3 $Floor1 ;
 node 417 $Pier4 $Floor1 ;
 node 517 $Pier5 $Floor1 ;

 # column hinges at top of Story 1
 node 126 $Pier1 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible ;
 node 226 $Pier2 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible;
 node 326 $Pier3 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible;
 node 426 $Pier4 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible;
 node 526 $Pier5 [expr $Floor2-$phlatcols1-$phlat23] -mass $Negligible $Negligible $Negligible;

 # column hinges at bottom of Story 2
 node 127 $Pier1 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
 node 227 $Pier2 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
 node 327 $Pier3 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
 node 427 $Pier4 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
 node 527 $Pier5 [expr $Floor2+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;

 # column hinges at top of Story 2
 node 136 $Pier1 [expr $Floor3-$phlatcols1-$phlat23]
 node 236 $Pier2 [expr $Floor3-$phlatcols1-$phlat23]
 node 336 $Pier3 [expr $Floor3-$phlatcols1-$phlat23]
 node 436 $Pier4 [expr $Floor3-$phlatcols1-$phlat23]
 node 536 $Pier5 [expr $Floor3-$phlatcols1-$phlat23]

 # column hinges at bottom of Story 3
 node 137 $Pier1 [expr $Floor3+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
 node 237 $Pier2 [expr $Floor3+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
 node 337 $Pier3 [expr $Floor3+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
 node 437 $Pier4 [expr $Floor3+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
 node 537 $Pier5 [expr $Floor3+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;

 # column hinges at top of Story 3
 node 146 $Pier1 [expr $Floor4-$phlatcols1-$phlat23]
 node 246 $Pier2 [expr $Floor4-$phlatcols1-$phlat23]
 node 346 $Pier3 [expr $Floor4-$phlatcols1-$phlat23]
 node 446 $Pier4 [expr $Floor4-$phlatcols1-$phlat23]
 node 546 $Pier5 [expr $Floor4-$phlatcols1-$phlat23]
```

```
    # column hinges at bottom of Story 4
    node 147 $Pier1 [expr $Floor4+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
    node 247 $Pier2 [expr $Floor4+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
    node 347 $Pier3 [expr $Floor4+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
    node 447 $Pier4 [expr $Floor4+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;
    node 547 $Pier5 [expr $Floor4+$phlatcols1+$phlat23] -mass $Negligible $Negligible $Negligible;

    # column hinges at top of Story 4
    node 156 $Pier1 [expr $Floor5-$phlatcols1-$phlat23]
    node 256 $Pier2 [expr $Floor5-$phlatcols1-$phlat23]
    node 356 $Pier3 [expr $Floor5-$phlatcols1-$phlat23]
    node 456 $Pier4 [expr $Floor5-$phlatcols1-$phlat23]
    node 556 $Pier5 [expr $Floor5-$phlatcols1-$phlat23]

################################################################
## Define Rigid Offsets for joints
################################################################

    # column hinges at top of Story 1
    node 10126 $Pier1 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10226 $Pier2 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10326 $Pier3 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10426 $Pier4 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10526 $Pier5 [expr $Floor2-$phlatcols1] -mass $Negligible $Negligible $Negligible;

    # column hinges at bottom of Story 2
    node 10127 $Pier1 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10227 $Pier2 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10327 $Pier3 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10427 $Pier4 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10527 $Pier5 [expr $Floor2+$phlatcols1] -mass $Negligible $Negligible $Negligible;

    # column hinges at top of Story 2
    node 10136 $Pier1 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10236 $Pier2 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10336 $Pier3 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10436 $Pier4 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10536 $Pier5 [expr $Floor3-$phlatcols1] -mass $Negligible $Negligible $Negligible;


    # column hinges at bottom of Story 3
    node 10137 $Pier1 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10237 $Pier2 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;
    node 10337 $Pier3 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;
```

```
node 10437 $Pier4 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10537 $Pier5 [expr $Floor3+$phlatcols1] -mass $Negligible $Negligible $Negligible;

# column hinges at top of Story 3
node 10146 $Pier1 [expr $Floor4-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10246 $Pier2 [expr $Floor4-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10346 $Pier3 [expr $Floor4-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10446 $Pier4 [expr $Floor4-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10546 $Pier5 [expr $Floor4-$phlatcols1] -mass $Negligible $Negligible $Negligible;

# column hinges at bottom of Story 4
node 10147 $Pier1 [expr $Floor4+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10247 $Pier2 [expr $Floor4+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10347 $Pier3 [expr $Floor4+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10447 $Pier4 [expr $Floor4+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10547 $Pier5 [expr $Floor4+$phlatcols1] -mass $Negligible $Negligible $Negligible;

# column hinges at top of Story 4
node 10156 $Pier1 [expr $Floor5-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10256 $Pier2 [expr $Floor5-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10356 $Pier3 [expr $Floor5-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10456 $Pier4 [expr $Floor5-$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10556 $Pier5 [expr $Floor5-$phlatcols1] -mass $Negligible $Negligible $Negligible;

# column hinges at bottom of Story 5
node 10157 $Pier1 [expr $Floor5+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10257 $Pier2 [expr $Floor5+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10357 $Pier3 [expr $Floor5+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10457 $Pier4 [expr $Floor5+$phlatcols1] -mass $Negligible $Negligible $Negligible;
node 10557 $Pier5 [expr $Floor5+$phlatcols1] -mass $Negligible $Negligible $Negligible;

# beam offset at Floor 2
node 9122 [expr $Pier1 - $phlatbeams2] $Floor2 -mass $Negligible $Negligible $Negligible;
node 9123 [expr $Pier1 + $phlatbeams2] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9222 [expr $Pier2 - $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9223 [expr $Pier2 + $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9322 [expr $Pier3 - $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9323 [expr $Pier3 + $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9422 [expr $Pier4 - $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
```

```
node 9423 [expr $Pier4 + $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9522 [expr $Pier5 - $phlatbeams1] $Floor2 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9523 [expr $Pier5 + $phlatbeams1] $Floor2 -mass $Negligible $Negligible $Negligible;

# beam offset at Floor 3
node 9132 [expr $Pier1 - $phlatbeams2] $Floor3 -mass $Negligible $Negligible $Negligible;
node 9133 [expr $Pier1 + $phlatbeams2] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9232 [expr $Pier2 - $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9233 [expr $Pier2 + $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9332 [expr $Pier3 - $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9333 [expr $Pier3 + $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9432 [expr $Pier4 - $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9433 [expr $Pier4 + $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9532 [expr $Pier5 - $phlatbeams1] $Floor3 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9533 [expr $Pier5 + $phlatbeams1] $Floor3 -mass $Negligible $Negligible $Negligible;

# beam offset at Floor 4
node 9142 [expr $Pier1 - $phlatbeams2] $Floor4 -mass $Negligible $Negligible $Negligible;
node 9143 [expr $Pier1 + $phlatbeams2] $Floor4 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9242 [expr $Pier2 - $phlatbeams1] $Floor4 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9243 [expr $Pier2 + $phlatbeams1] $Floor4 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9342 [expr $Pier3 - $phlatbeams1] $Floor4 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9343 [expr $Pier3 + $phlatbeams1] $Floor4 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9442 [expr $Pier4 - $phlatbeams1] $Floor4 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9443 [expr $Pier4 + $phlatbeams1] $Floor4 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9542 [expr $Pier5 - $phlatbeams1] $Floor4 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9543 [expr $Pier5 + $phlatbeams1] $Floor4 -mass $Negligible $Negligible $Negligible;

# beam offset at Floor 5
node 9152 [expr $Pier1 - $phlatbeams2] $Floor5 -mass $Negligible $Negligible $Negligible;
node 9153 [expr $Pier1 + $phlatbeams2] $Floor5 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9252 [expr $Pier2 - $phlatbeams1] $Floor5 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9253 [expr $Pier2 + $phlatbeams1] $Floor5 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9352 [expr $Pier3 - $phlatbeams1] $Floor5 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9353 [expr $Pier3 + $phlatbeams1] $Floor5 -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9452 [expr $Pier4 - $phlatbeams1] $Floor5 -mass [expr $NodalMass2/1] $Negligible $Negligible;
```

```
node 9453 [expr $Pier4 + $phlatbeams1] $Floor5  -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9552 [expr $Pier5 - $phlatbeams1] $Floor5  -mass [expr $NodalMass2/1] $Negligible $Negligible;
node 9553 [expr $Pier5 + $phlatbeams1] $Floor5  -mass $Negligible $Negligible $Negligible;

################################################################
################################################################

 # beam hinges at Floor 2
 node 123 [expr $Pier1 + $phlatbeams2 + $phlat23] $Floor2  -mass $Negligible $Negligible $Negligible;
 node 222 [expr $Pier2 - $phlatbeams1 + $phlat23] $Floor2  -mass $Negligible $Negligible $Negligible;
 node 223 [expr $Pier2 + $phlatbeams1 + $phlat23] $Floor2  -mass $Negligible $Negligible $Negligible;
 node 322 [expr $Pier3 - $phlatbeams1 + $phlat23] $Floor2  -mass $Negligible $Negligible $Negligible;
 node 323 [expr $Pier3 + $phlatbeams1 + $phlat23] $Floor2  -mass $Negligible $Negligible $Negligible;
 node 422 [expr $Pier4 - $phlatbeams1 + $phlat23] $Floor2  -mass $Negligible $Negligible $Negligible;
 node 423 [expr $Pier4 + $phlatbeams1 + $phlat23] $Floor2  -mass $Negligible $Negligible $Negligible;
 node 522 [expr $Pier5 - $phlatbeams1 + $phlat23] $Floor2  -mass $Negligible $Negligible $Negligible ;

 # beam hinges at Floor 3
 node 133 [expr $Pier1 + $phlatbeams2 + $phlat23] $Floor3  -mass $Negligible $Negligible $Negligible;
 node 232 [expr $Pier2 - $phlatbeams1 + $phlat23] $Floor3  -mass $Negligible $Negligible $Negligible;
 node 233 [expr $Pier2 + $phlatbeams1 + $phlat23] $Floor3  -mass $Negligible $Negligible $Negligible;
 node 332 [expr $Pier3 - $phlatbeams1 + $phlat23] $Floor3  -mass $Negligible $Negligible $Negligible;
 node 333 [expr $Pier3 + $phlatbeams1 + $phlat23] $Floor3  -mass $Negligible $Negligible $Negligible;
 node 432 [expr $Pier4 - $phlatbeams1 + $phlat23] $Floor3  -mass $Negligible $Negligible $Negligible;
 node 433 [expr $Pier4 + $phlatbeams1 + $phlat23] $Floor3  -mass $Negligible $Negligible $Negligible;
 node 532 [expr $Pier5 - $phlatbeams1 + $phlat23] $Floor3  -mass $Negligible $Negligible $Negligible;

 # beam hinges at Floor 4
 node 143 [expr $Pier1 + $phlatbeams2 + $phlat23] $Floor4  -mass $Negligible $Negligible $Negligible;
 node 242 [expr $Pier2 - $phlatbeams1 + $phlat23] $Floor4  -mass $Negligible $Negligible $Negligible;
 node 243 [expr $Pier2 + $phlatbeams1 + $phlat23] $Floor4  -mass $Negligible $Negligible $Negligible;
 node 342 [expr $Pier3 - $phlatbeams1 + $phlat23] $Floor4  -mass $Negligible $Negligible $Negligible;
 node 343 [expr $Pier3 + $phlatbeams1 + $phlat23] $Floor4  -mass $Negligible $Negligible $Negligible;
 node 442 [expr $Pier4 - $phlatbeams1 + $phlat23] $Floor4  -mass $Negligible $Negligible $Negligible;
 node 443 [expr $Pier4 + $phlatbeams1 + $phlat23] $Floor4  -mass $Negligible $Negligible $Negligible;
 node 542 [expr $Pier5 - $phlatbeams1 + $phlat23] $Floor4  -mass $Negligible $Negligible $Negligible;

 # beam hinges at Floor 5
 node 153 [expr $Pier1 + $phlatbeams2 + $phlat23] $Floor5  -mass $Negligible $Negligible $Negligible;
```

```
  node 252 [expr $Pier2 - $phlatbeams1 + $phlat23] $Floor5  -mass $Negligible
      $Negligible $Negligible;
  node 253 [expr $Pier2 + $phlatbeams1 + $phlat23] $Floor5  -mass $Negligible
      $Negligible $Negligible;
  node 352 [expr $Pier3 - $phlatbeams1 + $phlat23] $Floor5  -mass $Negligible
      $Negligible $Negligible;
  node 353 [expr $Pier3 + $phlatbeams1 + $phlat23] $Floor5  -mass $Negligible
      $Negligible $Negligible;
  node 452 [expr $Pier4 - $phlatbeams1 + $phlat23] $Floor5  -mass $Negligible
      $Negligible $Negligible;
  node 453 [expr $Pier4 + $phlatbeams1 + $phlat23] $Floor5  -mass $Negligible
      $Negligible $Negligible;
  node 552 [expr $Pier5 - $phlatbeams1 + $phlat23] $Floor5  -mass $Negligible
      $Negligible $Negligible;

  uniaxialMaterial Elastic 666 [expr 50.*4500000.]

# Create rigid joints
  element Joint2D 7777712 10126 9123 10127 9122  12 666 1
  element Joint2D 7777713 10136 9133 10137 9132  13 666 1
  element Joint2D 7777714 10146 9143 10147 9142  14 666 1
  element Joint2D 7777715 10156 9153 10157 9152  15 666 1

  element Joint2D 7777722 10226 9223 10227 9222 22 666 1
  element Joint2D 7777723 10236 9233 10237 9232 23 666 1
  element Joint2D 7777724 10246 9243 10247 9242 24 666 1
  element Joint2D 7777725 10256 9253 10257 9252 25 666 1

  element Joint2D 7777732 10326 9323 10327 9322 32 666 1
  element Joint2D 7777733 10336 9333 10337 9332 33 666 1
  element Joint2D 7777734 10346 9343 10347 9342 34 666 1
  element Joint2D 7777735 10356 9353 10357 9352 35 666 1

  element Joint2D 7777742 10426 9423 10427 9422 42 666 1
  element Joint2D 7777743 10436 9433 10437 9432 43 666 1
  element Joint2D 7777744 10446 9443 10447 9442 44 666 1
  element Joint2D 7777745 10456 9453 10457 9452 45 666 1

  element Joint2D 7777752 10526 9523 10527 9522 52 666 1
  element Joint2D 7777753 10536 9533 10537 9532 53 666 1
  element Joint2D 7777754 10546 9543 10547 9542 54 666 1
  element Joint2D 7777755 10556 9553 10557 9552 55 666 1

# assign boundary condidtions
  # command:  fix nodeID dxFixity dyFixity rzFixity
  # fixity values: 1 = constrained; 0 = unconstrained
  # fix the base of the building; pin P-delta column at base

  fix 11 1 1 1;
  fix 21 1 1 1;
  fix 31 1 1 1;
  fix 41 1 1 1;
  fix 51 1 1 1;

######################################################################
#          Define Section Properties and Elements
######################################################################
# define material properties
  set Ec 3600.;     # concrete Young's modulus

# set up geometric transformations of element
  set PDeltaTransf 10;
  geomTransf PDelta $PDeltaTransf ;   # PDelta transformation

  set LinearTransf  20;
  geomTransf Linear  $LinearTransf;   # PDelta transformation

################################################################
################################################################
#          Column Elements Properties
################################################################
################################################################

################################################################
```

```
#           General Properties of Column Cross Sections
##############################################################

  set Ec 3600.; # concrete Young's modulus

# Interior Columns
  set Acol_123  324.; # cross-sectional area
  set modcolscrack1 0.3  ; #if 1 cracking of elastic section of beam not taken into account - if 0.3 taken into account
  set Icol_123  [expr $modcolscrack1* 8748.]; # moment of inertia

#Exterior Columns
  set Acol_1231  324.; # cross-sectional area
  set modcolscrack1 0.3  ; #if 1 cracking of elastic section of beam not taken into account - if 0.3 taken into account
  set Icol_1231  [expr $modcolscrack1* 8748.];  # moment of inertia

  set w1 18
  set h1 18

# define column section 20"x20" for Storey 4,5 & 6

#Interior Columns
  set Acol_456  324.;   # cross-sectional area
  set modcolscrack2 0.3  ;  #if 1 cracking of elastic section of beam not taken into account - if 0.3 taken into account
  set Icol_456  [expr $modcolscrack2* 8748.]; # moment of inertia
#Exterior Columns
  set Acol_4561  324.;    # cross-sectional area
  set modcolscrack2 0.3  ;  #if 1 cracking of elastic section of beam not taken into account - if 0.3 taken into account
  set Icol_4561  [expr $modcolscrack2* 8748.];  # moment of inertia

  set w2 18
  set h2 18

  set rho1int 0.00102 ;
  set Fsw1int 17.     ;
  set rho2int 0.00102 ;
  set Fsw2int 17.     ;
  set rho3int 0.00102 ;
  set Fsw3int 17.     ;
  set rho4int 0.00102 ;
  set Fsw4int 17.     ;

  set rho1ext 0.00102 ;
  set Fsw1ext 17.     ;
  set rho2ext 0.00102 ;
  set Fsw2ext 17.     ;
  set rho3ext 0.00102 ;
  set Fsw3ext 17.     ;
  set rho4ext 0.00102 ;
  set Fsw4ext 17.     ;

  # determine stiffness modifications to equate the stiffness of the spring-elastic element-spring subassembly to the stiffness of the actual frame member
  # Reference:  Ibarra, L. F., and Krawinkler, H. (2005). "Global collapse of frame structures under seismic excitations," Technical Report 152,
  #             The John A. Blume Earthquake Engineering Research Center, Department of Civil Engineering, Stanford University, Stanford, CA.
  # calculate modified section properties to account for spring stiffness being in series with the elastic element stiffness
  set n 10.0;   # stiffness multiplier for rotational spring
  set n1 100.0 ;  # stiffness multiplier for shear and axial spring

  # calculate modified moment of inertia for elastic elements
  #Interior
  set Icol_123mod  [expr $Icol_123*($n+1.0)/$n];  # modified moment of inertia for columns in Story 1,2 & 3
  set Icol_456mod  [expr $Icol_456*($n+1.0)/$n];  # modified moment of inertia for columns in Story 2,3 & 4

  #Exterior
  set Icol_1231mod  [expr $Icol_1231*($n+1.0)/$n];  # modified moment of inertia for columns in Story 1,2 & 3
```

```
  set Icol_4561mod  [expr $Icol_4561*($n+1.0)/$n];  # modified moment of inertia for columns in Story 2,3 & 4

  # calculate modified rotational stiffness for plastic hinge springs
  #Interior
  set Ks_col_1123   [expr $n*6.0*$Ec*$Icol_123mod/$HStory1];    # rotational stiffness of Story 1 column springs
  set Ks_col_2123   [expr $n*6.0*$Ec*$Icol_123mod/$HStoryTyp];  # rotational stiffness of Story 2 column springs
  set Ks_col_1456   [expr $n*6.0*$Ec*$Icol_456mod/$HStoryTyp];  # rotational stiffness of Story 2 column springs

  #Exterior
  set Ks_col_11231   [expr $n*6.0*$Ec*$Icol_1231mod/$HStory1];    # rotational stiffness of Story 1 column springs
  set Ks_col_21231   [expr $n*6.0*$Ec*$Icol_1231mod/$HStoryTyp];  # rotational stiffness of Story 2 column springs
  set Ks_col_14561   [expr $n*6.0*$Ec*$Icol_4561mod/$HStoryTyp];  # rotational stiffness of Story 2 column springs


##################################################################
# Parameters for Shear Limit State Material
##################################################################

  set s1psh 10.0
  set s2psh 20.0
  set s3psh 90.0
  set s1nsh -10.0
  set s2nsh -20.0
  set s3nsh -90.0
  set pinchXsh 0.5
  set pinchYsh 0.5
    set damage1sh 0.05
  set damage2sh 0.05
  set betash 0
  set curveTypesh 2

  set Av_123 [expr (5./6.)*$Acol_123];
  set Av_456 [expr (5./6.)*$Acol_123];

  set Ksh_col_1123   [expr ($Ec/2.3)*$Av_123/$HStory1]; # Shear Stifness G*Av/L
  set Ksh_col_2123   [expr ($Ec/2.3)*$Av_123/$HStoryTyp]; # Shear Stifness G*Av/L
  set Ksh_col_1456   [expr ($Ec/2.3)*$Av_456/$HStoryTyp]; # Shear Stifness G*Av/L

  set Ksf_1i  [expr -100.];
  set Ksf_1e  [expr -100.];

  set Ksf_2i  [expr -100.];
  set Ksf_2e  [expr -100.];

  set Ksf_3i  [expr -100.];
  set Ksf_3e  [expr -100.];

  set Ksf_4i  [expr -100.];
  set Ksf_4e  [expr -100.];

##################################################################
# Parameters for Axial Limit State Material
##################################################################

  set s1pax 10.0
  set s2pax 30.0
  set s3pax 90.0
  set s1nax -10.0
  set s2nax -30.0
  set s3nax -90.0
  set pinchXax 0.5
  set pinchYax 0.5
    set damage1ax 0.05
  set damage2ax 0.05
  set betaax 0.0
  set curveTypeax 1
```

```
    set Kax_col_1123   [expr $n1*$Ec*$Acol_123/$HStory1];   # rotational stiffness of Story 1 column springs
    set Kax_col_2123   [expr $n1*$Ec*$Acol_123/$HStoryTyp]; # rotational stiffness of Story 2 column springs
    set Kax_col_1456   [expr $n1*$Ec*$Acol_456/$HStoryTyp]; # rotational stiffness of Story 2 column springs

    set Kad_col_1123   [expr -0.01*$Ec*$Acol_123/$HStory1];   # rotational stiffness of Story 1 column springs
    set Kad_col_2123   [expr -0.01*$Ec*$Acol_123/$HStoryTyp]; # rotational stiffness of Story 2 column springs
    set Kad_col_1456   [expr -0.01*$Ec*$Acol_456/$HStoryTyp]; # rotational stiffness of Story 2 column springs

# define elastic column elements using "element" command

    # command: element elasticBeamColumn $eleID $iNode $jNode $A $E $I $transfID
    # eleID convention:  "1xy" where 1 = col, x = Pier #, y = Story #
    # Columns Story 1
    element elasticBeamColumn  111  117 126 $Acol_123 $Ec  $Icol_1231mod  $PDeltaTransf;  # Pier 1
    element elasticBeamColumn  121  217 226 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 2
    element elasticBeamColumn  131  317 326 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 3
    element elasticBeamColumn  141  417 426 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 4
    element elasticBeamColumn  151  517 526 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 5

    # Columns Story 2
    element elasticBeamColumn  112  127 136 $Acol_123 $Ec  $Icol_1231mod  $PDeltaTransf;  # Pier 1
    element elasticBeamColumn  122  227 236 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 2
    element elasticBeamColumn  132  327 336 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 3
    element elasticBeamColumn  142  427 436 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 4
    element elasticBeamColumn  152  527 536 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 5

    # Columns Story 3
    element elasticBeamColumn  113  137 146 $Acol_123 $Ec  $Icol_1231mod  $PDeltaTransf;  # Pier 1
    element elasticBeamColumn  123  237 246 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 2
    element elasticBeamColumn  133  337 346 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 3
    element elasticBeamColumn  143  437 446 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 4
    element elasticBeamColumn  153  537 546 $Acol_123 $Ec  $Icol_123mod  $PDeltaTransf;  # Pier 5

    # Columns Story 4
    element elasticBeamColumn  114  147 156 $Acol_456 $Ec  $Icol_4561mod  $PDeltaTransf;  # Pier 1
    element elasticBeamColumn  124  247 256 $Acol_456 $Ec  $Icol_456mod  $PDeltaTransf;  # Pier 2
    element elasticBeamColumn  134  347 356 $Acol_456 $Ec  $Icol_456mod  $PDeltaTransf;  # Pier 3
    element elasticBeamColumn  144  447 456 $Acol_456 $Ec  $Icol_456mod  $PDeltaTransf;  # Pier 4
    element elasticBeamColumn  154  547 556 $Acol_456 $Ec  $Icol_456mod  $PDeltaTransf;  # Pier 5

    uniaxialMaterial Elastic 1 99.9

#Column Hinge Properties
# General input values for Column springs

```

```
set LS1 0.0; # basic strength deterioration (a very large  # = no cyclic deterioration)
set LK1 0.0; # unloading stiffness deterioration (a very large # = no cyclic deterioration)
set LA1 0.0; # accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
set LD1 0.0; # post-capping strength deterioration (a very large # = no deterioration)

set LS2 0.0; # basic strength deterioration (a very large  # = no cyclic deterioration)
set LK2 0.0; # unloading stiffness deterioration (a very large # = no cyclic deterioration)
set LA2 0.0; # accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
set LD2 0.0; # post-capping strength deterioration (a very large # = no deterioration)

set LS3 0.0; # basic strength deterioration (a very large  # = no cyclic deterioration)
set LK3 0.0; # unloading stiffness deterioration (a very large # = no cyclic deterioration)
set LA3 0.0; # accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
set LD3 0.0; # post-capping strength deterioration (a very large # = no deterioration)

set LS4 0.0; # basic strength deterioration (a very large  # = no cyclic deterioration)
set LK4 0.0; # unloading stiffness deterioration (a very large # = no cyclic deterioration)
set LA4 0.0; # accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
set LD4 0.0; # post-capping strength deterioration (a very large # = no deterioration)

set cS 1.0; # exponent for basic strength deterioration (c = 1.0 for no deterioration)
set cK 1.0; # exponent for unloading stiffness deterioration (c = 1.0 for no deterioration)
set cA 1.0; # exponent for accelerated reloading stiffness deterioration (c = 1.0 for no deterioration)
set cD 1.0; # exponent for post-capping strength deterioration (c = 1.0 for no deterioration)

set th_pc1P 10.0;     # post-capping rot capacity for pos loading
set th_pc1N 10.0;     # post-capping rot capacity for neg loading
set th_pc2P 10.0;     # post-capping rot capacity for pos loading
  set th_pc2N 10.0;     # post-capping rot capacity for neg loading
set th_pc3P 10.0;     # post-capping rot capacity for pos loading
set th_pc3N 10.0;     # post-capping rot capacity for neg loading
set th_pc4P 10.0;     # post-capping rot capacity for pos loading
  set th_pc4N 10.0;     # post-capping rot capacity for neg loading

set ResP 1.00;      # residual strength ratio for pos loading
set ResN 1.00;      # residual strength ratio for neg loading
set th_uP 10.1;     # ultimate rot capacity for pos loading
set th_uN 10.1;     # ultimate rot capacity for neg loading

set DP 1.0;       # rate of cyclic deterioration for pos loading
set DN 1.0;       # rate of cyclic deterioration for neg loading

set McMy1 1.20
set McMy2 1.20

set th_p1P 0.048;
set th_p1N 0.048;
set th_p2P 0.060;
set th_p2N 0.060;
set th_p3P 0.060;
```

```
    set th_p3N 0.060;
    set th_p4P 0.064;
    set th_p4N 0.064;

    set My_c1i 3000.
    set My_c2i 2900.
    set My_c3i 2750.
    set My_c4i 2650.

    set My_c1e 2750.
    set My_c2e 2700.
    set My_c3e 2650.
    set My_c4e 2600.

# define column springs
    # Spring ID: "3xya", where 3 = col spring, x = Pier #, y = Story #, a = location in story
    # "a" convention: 1 = bottom of story, 2 = top of story
    # command: rotSpring2DModIKModel id ndR ndC K McMy MyPos MyNeg LS LK LA LD cS cK cA cD th_p+ th_p- th_pc+ th_pc- Res+ Res- th_u+ th_u- D+ D-

# col springs @ bottom of Story 1 (at base)
    rotSpring2DModIKModel 3111 11 117 $Ks_col_11231 $McMy1 [expr $My_c1e] [expr -$My_c1e] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 3211 21 217 $Ks_col_1123 $McMy1 [expr $My_c1i] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 3311 31 317 $Ks_col_1123 $McMy1 [expr $My_c1i] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 3411 41 417 $Ks_col_1123 $McMy1 [expr $My_c1i] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 3511 51 517 $Ks_col_11231 $McMy1 [expr $My_c1e] [expr -$My_c1e] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN;

#col springs @ top of Story 1 (below Floor 2)
    rotSpring2DModIKModel2 3112 10126 126 $w1 $h1 $Ks_col_11231 $McMy1 [expr $My_c1e] [expr -$My_c1e] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr $s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1ext $Fsw1ext $Ksf_1e\
    $s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123

    rotSpring2DModIKModel2 3212 10226 226 $w1 $h1 $Ks_col_1123 $McMy1 [expr $My_c1i] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr $s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1int $Fsw1int $Ksf_1i\
    $s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123
    rotSpring2DModIKModel2 3312 10326 326 $w1 $h1 $Ks_col_1123 $McMy1 [expr $My_c1i] [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr
```

```
$s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1int $Fsw1int $Ksf_1i\
$s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123
rotSpring2DModIKModel2 3412 10426 426 $w1 $h1 $Ks_col_1123  $McMy1   [expr $My_c1i]  [expr -$My_c1i] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr $s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1int $Fsw1int $Ksf_1i\
$s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123
rotSpring2DModIKModel2 3512 10526 526 $w1 $h1 $Ks_col_11231  $McMy1    [expr $My_c1e]  [expr -$My_c1e ] $LS1 $LK1 $LA1 $LD1 $cS $cK $cA $cD $th_p1P $th_p1N $th_pc1P $th_pc1N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1123] $s2psh [expr $s2psh/$Ksh_col_1123] $s3psh [expr $s3psh/$Ksh_col_1123] $s1nsh [expr $s1nsh/$Ksh_col_1123] $s2nsh [expr $s2nsh/$Ksh_col_1123] $s3nsh [expr $s3nsh/$Ksh_col_1123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho1int $Fsw1int $Ksf_1e\
$s1pax [expr $s1pax/$Kax_col_1123] $s2pax [expr $s2pax/$Kax_col_1123] $s3pax [expr $s3pax/$Kax_col_1123] $s1nax [expr $s1nax/$Kax_col_1123] $s2nax [expr $s2nax/$Kax_col_1123] $s3nax [expr $s3nax/$Kax_col_1123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1123

# col springs @ bottom of Story 2 (above Floor 2)
rotSpring2DModIKModel 3121 10127 127 $Ks_col_21231 $McMy1   [expr $My_c2e]    [expr -$My_c2e ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;
rotSpring2DModIKModel 3221 10227 227 $Ks_col_2123  $McMy1   [expr $My_c2i ]    [expr -$My_c2i ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;
rotSpring2DModIKModel 3321 10327 327 $Ks_col_2123  $McMy1   [expr $My_c2i ]    [expr -$My_c2i ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;
rotSpring2DModIKModel 3421 10427 427 $Ks_col_2123  $McMy1   [expr $My_c2i ]    [expr -$My_c2i ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;
rotSpring2DModIKModel 3521 10527 527 $Ks_col_21231  $McMy1   [expr $My_c2e]    [expr -$My_c2e ] $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN;

#col springs @ top of Story 2 (below Floor 3)
rotSpring2DModIKModel2 3122 10136 136 $w1 $h1 $Ks_col_21231 $McMy1  [expr $My_c2e]    [expr -$My_c2e ]        $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho2ext $Fsw2ext $Ksf_2e\
$s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123
rotSpring2DModIKModel2 3222 10236 236 $w1 $h1 $Ks_col_2123  $McMy1  [expr $My_c2i]    [expr -$My_c2i ]        $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN  $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho2int $Fsw2int $Ksf_2i\
```

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    $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123
    rotSpring2DModIKModel2 3322 10336 336 $w1 $h1 $Ks_col_2123  $McMy1   [expr $My_c2i ]    [expr -$My_c2i ]          $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho2int $Fsw2int $Ksf_2i\
    $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123;
    rotSpring2DModIKModel2 3422 10436 436 $w1 $h1 $Ks_col_2123  $McMy1   [expr $My_c2i ]    [expr -$My_c2i ]          $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho2int $Fsw2int $Ksf_2i\
    $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123;
    rotSpring2DModIKModel2 3522 10536 536 $w1 $h1 $Ks_col_21231  $McMy1   [expr $My_c2e ]    [expr -$My_c2e ]          $LS2 $LK2 $LA2 $LD2 $cS $cK $cA $cD $th_p2P $th_p2N $th_pc2P $th_pc2N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho2int $Fsw2int $Ksf_2e\
    $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_212

# col springs @ bottom of Story 3 (above Floor 3)
    rotSpring2DModIKModel 3131 10137 137 $Ks_col_21231 $McMy1  [expr $My_c3e]     [expr -$My_c3e ] $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN ;
    rotSpring2DModIKModel 3231 10237 237 $Ks_col_2123  $McMy1  [expr $My_c3i]     [expr -$My_c3i ] $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 3331 10337 337 $Ks_col_2123  $McMy1  [expr $My_c3i]     [expr -$My_c3i ] $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN ;
    rotSpring2DModIKModel 3431 10437 437 $Ks_col_2123  $McMy1  [expr $My_c3i]     [expr -$My_c3i ] $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN ;
    rotSpring2DModIKModel 3531 10537 537 $Ks_col_21231  $McMy1  [expr $My_c3e]     [expr -$My_c3e ] $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN ;

#col springs @ top of Story 3 (below Floor 4)
    rotSpring2DModIKModel2 3132 10146 146 $w1 $h1 $Ks_col_21231 $McMy1   [expr $My_c3e]     [expr -$My_c3e]          $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho3ext $Fsw3ext $Ksf_3e\
    $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/
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$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123
  rotSpring2DModIKModel2 3232 10246 246 $w1 $h1 $Ks_col_2123  $McMy1   [expr $My_c3i] [expr -$My_c3i ]          $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho3ext $Fsw3ext $Ksf_3i\
  $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123
  rotSpring2DModIKModel2 3332 10346 346 $w1 $h1 $Ks_col_2123  $McMy1   [expr $My_c3i] [expr -$My_c3i ] $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho3ext $Fsw3ext $Ksf_3i\
  $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123
  rotSpring2DModIKModel2 3432 10446 446 $w1 $h1 $Ks_col_2123  $McMy1   [expr $My_c3i] [expr -$My_c3i ] $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho3ext $Fsw3ext $Ksf_3i\
  $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123
  rotSpring2DModIKModel2 3532 10546 546 $w1 $h1 $Ks_col_21231  $McMy1   [expr $My_c3e ]      [expr -$My_c3e] $LS3 $LK3 $LA3 $LD3 $cS $cK $cA $cD $th_p3P $th_p3N $th_pc3P $th_pc3N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_2123] $s2psh [expr $s2psh/$Ksh_col_2123] $s3psh [expr $s3psh/$Ksh_col_2123] $s1nsh [expr $s1nsh/$Ksh_col_2123] $s2nsh [expr $s2nsh/$Ksh_col_2123] $s3nsh [expr $s3nsh/$Ksh_col_2123] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho3ext $Fsw3ext $Ksf_3e\
  $s1pax [expr $s1pax/$Kax_col_2123] $s2pax [expr $s2pax/$Kax_col_2123] $s3pax [expr $s3pax/$Kax_col_2123] $s1nax [expr $s1nax/$Kax_col_2123] $s2nax [expr $s2nax/$Kax_col_2123] $s3nax [expr $s3nax/$Kax_col_2123] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_2123

# col springs @ bottom of Story 4 (above Floor 4)
  rotSpring2DModIKModel 3141 10147 147 $Ks_col_14561 $McMy2   [expr $My_c4e]     [expr -$My_c4e ]   $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 3241 10247 247 $Ks_col_1456  $McMy2   [expr $My_c4i ]     [expr -$My_c4i ]   $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 3341 10347 347 $Ks_col_1456  $McMy2   [expr $My_c4i ]     [expr -$My_c4i ]   $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 3441 10447 447 $Ks_col_1456  $McMy2   [expr $My_c4i ]     [expr -$My_c4i ]   $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 3541 10547 547 $Ks_col_14561  $McMy2   [expr $My_c4e]     [expr -$My_c4e ]  $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN;

#col springs @ top of Story 4 (below Floor 5)
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    rotSpring2DModIKModel2 3142 10156 156 $w2 $h2 $Ks_col_14561 $McMy2 [expr $My_c4e ] [expr -$My_c4e ] $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1456] $s2psh [expr $s2psh/$Ksh_col_1456] $s3psh [expr $s3psh/$Ksh_col_1456] $s1nsh [expr $s1nsh/$Ksh_col_1456] $s2nsh [expr $s2nsh/$Ksh_col_1456] $s3nsh [expr $s3nsh/$Ksh_col_1456] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho4ext $Fsw4ext $Ksf_4e\
    $s1pax [expr $s1pax/$Kax_col_1456] $s2pax [expr $s2pax/$Kax_col_1456] $s3pax [expr $s3pax/$Kax_col_1456] $s1nax [expr $s1nax/$Kax_col_1456] $s2nax [expr $s2nax/$Kax_col_1456] $s3nax [expr $s3nax/$Kax_col_1456] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1456
    rotSpring2DModIKModel2 3242 10256 256 $w2 $h2 $Ks_col_1456 $McMy2 [expr $My_c4i ] [expr -$My_c4i ] $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1456] $s2psh [expr $s2psh/$Ksh_col_1456] $s3psh [expr $s3psh/$Ksh_col_1456] $s1nsh [expr $s1nsh/$Ksh_col_1456] $s2nsh [expr $s2nsh/$Ksh_col_1456] $s3nsh [expr $s3nsh/$Ksh_col_1456] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho4int $Fsw4int $Ksf_4i\
    $s1pax [expr $s1pax/$Kax_col_1456] $s2pax [expr $s2pax/$Kax_col_1456] $s3pax [expr $s3pax/$Kax_col_1456] $s1nax [expr $s1nax/$Kax_col_1456] $s2nax [expr $s2nax/$Kax_col_1456] $s3nax [expr $s3nax/$Kax_col_1456] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1456
    rotSpring2DModIKModel2 3342 10356 356 $w2 $h2 $Ks_col_1456 $McMy2 [expr $My_c4i ] [expr -$My_c4i ] $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1456] $s2psh [expr $s2psh/$Ksh_col_1456] $s3psh [expr $s3psh/$Ksh_col_1456] $s1nsh [expr $s1nsh/$Ksh_col_1456] $s2nsh [expr $s2nsh/$Ksh_col_1456] $s3nsh [expr $s3nsh/$Ksh_col_1456] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho4int $Fsw4int $Ksf_4i\
    $s1pax [expr $s1pax/$Kax_col_1456] $s2pax [expr $s2pax/$Kax_col_1456] $s3pax [expr $s3pax/$Kax_col_1456] $s1nax [expr $s1nax/$Kax_col_1456] $s2nax [expr $s2nax/$Kax_col_1456] $s3nax [expr $s3nax/$Kax_col_1456] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1456
    rotSpring2DModIKModel2 3442 10456 456 $w2 $h2 $Ks_col_1456 $McMy2 [expr $My_c4i ] [expr -$My_c4i ] $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1456] $s2psh [expr $s2psh/$Ksh_col_1456] $s3psh [expr $s3psh/$Ksh_col_1456] $s1nsh [expr $s1nsh/$Ksh_col_1456] $s2nsh [expr $s2nsh/$Ksh_col_1456] $s3nsh [expr $s3nsh/$Ksh_col_1456] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho4int $Fsw4int $Ksf_4i\
    $s1pax [expr $s1pax/$Kax_col_1456] $s2pax [expr $s2pax/$Kax_col_1456] $s3pax [expr $s3pax/$Kax_col_1456] $s1nax [expr $s1nax/$Kax_col_1456] $s2nax [expr $s2nax/$Kax_col_1456] $s3nax [expr $s3nax/$Kax_col_1456] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1456
    rotSpring2DModIKModel2 3542 10556 556 $w2 $h2 $Ks_col_14561 $McMy2 [expr $My_c4e ] [expr -$My_c4e ] $LS4 $LK4 $LA4 $LD4 $cS $cK $cA $cD $th_p4P $th_p4N $th_pc4P $th_pc4N $ResP $ResN $th_uP $th_uN $DP $DN $s1psh [expr $s1psh/$Ksh_col_1456] $s2psh [expr $s2psh/$Ksh_col_1456] $s3psh [expr $s3psh/$Ksh_col_1456] $s1nsh [expr $s1nsh/$Ksh_col_1456] $s2nsh [expr $s2nsh/$Ksh_col_1456] $s3nsh [expr $s3nsh/$Ksh_col_1456] $pinchXsh $pinchYsh $damage1sh $damage2sh $betash $curveTypesh $rho4int $Fsw4int $Ksf_4e\
    $s1pax [expr $s1pax/$Kax_col_1456] $s2pax [expr $s2pax/$Kax_col_1456] $s3pax [expr $s3pax/$Kax_col_1456] $s1nax [expr $s1nax/$Kax_col_1456] $s2nax [expr $s2nax/$Kax_col_1456] $s3nax [expr $s3nax/$Kax_col_1456] $pinchXax $pinchYax $damage1ax $damage2ax $betaax $curveTypeax $Kad_col_1456

##################################################################
##################################################################
#            Beam Elements Properties
##################################################################
##################################################################

##################################################################
#            General Properties of Beam Cross Sections
##################################################################
    set Ec 3600.; # concrete Young's modulus

# define beam section 18"x28" for Floor 2,3 & 4
```

```
  set modbeamscrack 0.6
 set Abeam_234  504.; # cross-sectional area (full section properties)
 set Ibeam_234  [expr $modbeamscrack*32928.];  # moment of inertia  (full section properties)

# define beam section 16"x28" for Floor 5,6 & 7
# set Abeam_567  448;   # cross-sectional area (full section properties)

 set Abeam_567  504.; # cross-sectional area (full section properties)
 set Ibeam_567  [expr $modbeamscrack*32928.]; # moment of inertia  (full section properties)

# determine stiffness modifications to equate the stiffness of the spring-elastic element-spring subassembly to the stiffness of the actual frame member
 # Reference:  Ibarra, L. F., and Krawinkler, H. (2005). "Global collapse of frame structures under seismic excitations," Technical Report 152,
 #             The John A. Blume Earthquake Engineering Research Center, Department of Civil Engineering, Stanford University, Stanford, CA.
 # calculate modified section properties to account for spring stiffness being in series with the elastic element stiffness
 set n 10.0;   # stiffness multiplier for rotational spring

 # calculate modified moment of inertia for elastic elements

 set Ibeam_234mod [expr $Ibeam_234*($n+1.0)/$n]; # modified moment of inertia for beams in Floor 2,3 & 4
 set Ibeam_567mod [expr $Ibeam_567*($n+1.0)/$n]; # modified moment of inertia for beams in Floor 5,6 & 7


 set Ks_beam_1234 [expr $n*6.0*$Ec*$Ibeam_234mod/$Wbay1]; # rotational stiffness of Floor 2,3 & 4 beam springs
 set Ks_beam_2234 [expr $n*6.0*$Ec*$Ibeam_234mod/$Wbay2]; # rotational stiffness of Floor 2,3 & 4 beam springs
 set Ks_beam_1567 [expr $n*6.0*$Ec*$Ibeam_567mod/$Wbay1]; # rotational stiffness of Floor 2,3 & 4 beam springs
 set Ks_beam_2567 [expr $n*6.0*$Ec*$Ibeam_567mod/$Wbay2]; # rotational stiffness of Floor 2,3 & 4 beam springs

# Elastic Beam Column Elements

 # eleID convention:  "2xy"  where 2 = beam, x = Bay #, y = Floor #
 # Beams Story 1
 element elasticBeamColumn  212  123 222 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
 element elasticBeamColumn  222  223 322 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
 element elasticBeamColumn  232  323 422 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
 element elasticBeamColumn  242  423 522 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;

 # Beams Story 2
 element elasticBeamColumn  213  133 232 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
 element elasticBeamColumn  223  233 332 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
 element elasticBeamColumn  233  333 432 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;
 element elasticBeamColumn  243  433 532 $Abeam_234 $Ec  $Ibeam_234mod $LinearTransf;

 # Beams Story 3
 element elasticBeamColumn  214  143 242 $Abeam_234 $Ec $Ibeam_234mod $LinearTransf;
 element elasticBeamColumn  224  243 342 $Abeam_234 $Ec $Ibeam_234mod $LinearTransf;
 element elasticBeamColumn  234  343 442 $Abeam_234 $Ec $Ibeam_234mod $LinearTransf;
 element elasticBeamColumn  244  443 542 $Abeam_234 $Ec $Ibeam_234mod $LinearTransf;
```

```
  # Beams Story 4
  element elasticBeamColumn  215  153 252 $Abeam_567 $Ec $Ibeam_567mod  $LinearTransf ;
  element elasticBeamColumn  225  253 352 $Abeam_567 $Ec $Ibeam_567mod  $LinearTransf ;
  element elasticBeamColumn  235  353 452 $Abeam_567 $Ec $Ibeam_567mod  $LinearTransf ;
  element elasticBeamColumn  245  453 552 $Abeam_567 $Ec $Ibeam_567mod  $LinearTransf ;

#################################################################
#            Define Rotational Springs for Plastic Hinges
#################################################################


# General input values for Beam Springs

  set LS13 64.0; # basic strength deterioration (a very large # = no cyclic deterioration)
  set LK13 0.0; # unloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LA13 0.0; # accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LD13 64.0; # post-capping strength deterioration (a very large # = no deterioration)

  set LS14 64.0; # basic strength deterioration (a very large # = no cyclic deterioration)
  set LK14 0.0; # unloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LA14 0.0; # accelerated reloading stiffness deterioration (a very large # = no cyclic deterioration)
  set LD14 64.0; # post-capping strength deterioration (a very large # = no deterioration)




  set cS 1.0; # exponent for basic strength deterioration (c = 1.0 for no deterioration)
  set cK 1.0; # exponent for unloading stiffness deterioration (c = 1.0 for no deterioration)
  set cA 1.0; # exponent for accelerated reloading stiffness deterioration (c = 1.0 for no deterioration)
  set cD 1.0; # exponent for post-capping strength deterioration (c = 1.0 for no deterioration)


  set th_pc13P 0.076; # post-capping rot capacity for pos loading
  set th_pc13N 0.076; # post-capping rot capacity for neg loading

  set th_pc14P 0.076; # post-capping rot capacity for pos loading
  set th_pc14N 0.076; # post-capping rot capacity for neg loading


  set ResP 0.10; # residual strength ratio for pos loading
  set ResN 0.10; # residual strength ratio for neg loading
  set th_uP 0.20; # ultimate rot capacity for pos loading
  set th_uN 0.20; # ultimate rot capacity for neg loading

  set DP 1.0; # rate of cyclic deterioration for pos loading
  set DN 1.0; # rate of cyclic deterioration for neg loading

  set McMy13 1.20
  set McMy14 1.20

  set th_p13P 0.049;
  set th_p13N 0.043;

  set th_p14P 0.046;
  set th_p14N 0.046;
```

```

  set My_bP 3550.
  set My_bN [expr -5750.]

#Story 1
#Defining Rotational Springs

#beam springs at Floor 2
  rotSpring2DModIKModel  4121 9123 123 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel  4122 9222 222 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel  4221 9223 223 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel  4222 9322 322 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel  4321 9323 323 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel  4322 9422 422 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel  4421 9423 423 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel  4422 9522 522 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;

# Story 2
  #beam springs at Floor 3
  rotSpring2DModIKModel 4131 9133 133 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4132 9232 232 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel 4231 9233 233 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4232 9332 332 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel 4331 9333 333 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4332 9432 432 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;
  rotSpring2DModIKModel 4431 9433 433 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4432 9532 532 $Ks_beam_1234 $McMy13  $My_bP $My_bN  $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN
      $ResP $th_uN $th_uP $DN $DP;

# Story 3
  #beam springs at Floor 4
  rotSpring2DModIKModel 4141 9143 143 $Ks_beam_1234 $McMy13  $My_bP $My_bN  $LS13
      $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP
      $ResN $th_uP $th_uN $DP $DN;
  rotSpring2DModIKModel 4142 9242 242 $Ks_beam_1234 $McMy13 $My_bP $My_bN $LS13 $LK13
       $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN $ResP
      $th_uN $th_uP $DN $DP;
```

```
    rotSpring2DModIKModel 4241 9243 243 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 4242 9342 342 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN $ResP $th_uN $th_uP $DN $DP;
    rotSpring2DModIKModel 4341 9343 343 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 4342 9442 442 $Ks_beam_2234 $McMy13  $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN $ResP $th_uN $th_uP $DN $DP;
    rotSpring2DModIKModel 4441 9443 443 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13P $th_p13N $th_pc13P $th_pc13N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 4442 9542 542 $Ks_beam_1234 $McMy13  $My_bP $My_bN $LS13 $LK13 $LA13 $LD13 $cS $cK $cA $cD $th_p13N $th_p13P $th_pc13N $th_pc13P $ResN $ResP $th_uN $th_uP $DN $DP;

# Story 4
  #beam springs at Floor 5
    rotSpring2DModIKModel 4151 9153 153 $Ks_beam_1567 $McMy14  $My_bP $My_bN    $LS14 $LK14 $LA14 $LD14 $cS $cK $cA $cD $th_p14P $th_p14N $th_pc14P $th_pc14N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 4152 9252 252 $Ks_beam_1567 $McMy14  $My_bP $My_bN $LS14 $LK14 $LA14 $LD14 $cS $cK $cA $cD $th_p14N $th_p14P $th_pc14N $th_pc14P $ResN $ResP $th_uN $th_uP $DN $DP;
    rotSpring2DModIKModel 4251 9253 253 $Ks_beam_2567 $McMy14  $My_bP $My_bN $LS14 $LK14 $LA14 $LD14 $cS $cK $cA $cD $th_p14P $th_p14N $th_pc14P $th_pc14N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 4252 9352 352 $Ks_beam_2567 $McMy14  $My_bP $My_bN $LS14 $LK14 $LA14 $LD14 $cS $cK $cA $cD $th_p14N $th_p14P $th_pc14N $th_pc14P $ResN $ResP $th_uN $th_uP $DN $DP;
    rotSpring2DModIKModel 4351 9353 353 $Ks_beam_2567 $McMy14  $My_bP $My_bN $LS14 $LK14 $LA14 $LD14 $cS $cK $cA $cD $th_p14P $th_p14N $th_pc14P $th_pc14N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 4352 9452 452 $Ks_beam_2567 $McMy14  $My_bP $My_bN $LS14 $LK14 $LA14 $LD14 $cS $cK $cA $cD $th_p14N $th_p14P $th_pc14N $th_pc14P $ResN $ResP $th_uN $th_uP $DN $DP;
    rotSpring2DModIKModel 4451 9453 453 $Ks_beam_1567 $McMy14  $My_bP $My_bN $LS14 $LK14 $LA14 $LD14 $cS $cK $cA $cD $th_p14P $th_p14N $th_pc14P $th_pc14N $ResP $ResN $th_uP $th_uN $DP $DN;
    rotSpring2DModIKModel 4452 9552 552 $Ks_beam_1567 $McMy14  $My_bP $My_bN $LS14 $LK14 $LA14 $LD14 $cS $cK $cA $cD $th_p14N $th_p14P $th_pc14N $th_pc14P $ResN $ResP $th_uN $th_uP $DN $DP;

###################################################################
#                 Gravity Loads & Gravity Analysis
###################################################################
# apply gravity loads
  #command: pattern PatternType $PatternID TimeSeriesType
  pattern Plain 1010 Constant {

    # command: load node Fx Fy Mz

      set P_PD1 [expr -$load_E]; # Pier 1
      set P_PD2 [expr -$load_I]; # Pier 2
      set P_PD3 [expr -$load_I]; # Pier 3
      set P_PD4 [expr -$load_I]; # Pier 4
      set P_PD5 [expr -$load_E]; # Pier 5

      load 10127 0.0 $P_PD1 0.0   ;    # Pier 1
      load 10227 0.0 $P_PD2 0.0   ;    # Pier 2
      load 10327 0.0 $P_PD3 0.0   ;    # Pier 3
      load 10427 0.0 $P_PD4 0.0   ;    # Pier 4
      load 10527 0.0 $P_PD5 0.0   ;    # Pier 5

      load 10137 0.0 $P_PD1 0.0   ;    # Pier 1
```

```
      load 10237 0.0 $P_PD2 0.0   ;   # Pier 2
      load 10337 0.0 $P_PD3 0.0   ;   # Pier 3
      load 10437 0.0 $P_PD4 0.0   ;   # Pier 4
      load 10537 0.0 $P_PD5 0.0   ;   # Pier 5

      load 10147 0.0 $P_PD1 0.0   ;   # Pier 1
      load 10247 0.0 $P_PD2 0.0   ;   # Pier 2
      load 10347 0.0 $P_PD3 0.0   ;   # Pier 3
      load 10447 0.0 $P_PD4 0.0   ;   # Pier 4
      load 10547 0.0 $P_PD5 0.0   ;   # Pier 5

      load 10157 0.0 $P_PD1 0.0   ;   # Pier 1
      load 10257 0.0 $P_PD2 0.0   ;   # Pier 2
      load 10357 0.0 $P_PD3 0.0   ;   # Pier 3
      load 10457 0.0 $P_PD4 0.0   ;   # Pier 4
      load 10557 0.0 $P_PD5 0.0   ;   # Pier 5
}

##################################################################
# define DAMPING
##################################################################
# apply Rayleigh DAMPING from $xDamp
# D=$alphaM*M + $betaKcurr*Kcurrent + $betaKcomm*KlastCommit + $beatKinit*$Kinitial

   set xDamp 0.02;       # 2% damping ratio

   set omega1 [expr 6.2832/$T1_damp]
   set omega3 [expr 6.2832/$T3_damp]

   set alpha1 [expr $xDamp*2*$omega1*$omega3/($omega1+$omega3)];
   set alpha2 [expr 2.*$xDamp/($omega1+$omega3)];

   set alphaM [expr $xDamp*2*$omega1*$omega3/($omega1+$omega3)]; # M-prop. damping; D = alphaM*M
   set betaKcurr 0.;              # K-proportional damping;      +beatKcurr*KCurrent
  # set betaKcomm [expr 2.*$xDamp/($omega)];    # K-prop. damping parameter;   +betaKcomm*KlastCommitt
  # set betaKinit 0.;              # initial-stiffness proportional damping      +beatKinit*Kini
   set betaKcomm 0.;     # K-prop. damping parameter;   +betaKcomm*KlastCommitt
   set betaKinit [expr 2.*$xDamp/($omega1+$omega3)];              # initial-stiffness proportional damping      +beatKinit*Kini
   set betaKinit_mod [expr $betaKinit*1.1];

# define damping

# Beam Regions by Bay
   region 555 -eleRange 212 215 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
   region 556 -eleRange 222 225 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
   region 557 -eleRange 232 235 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
   region 558 -eleRange 242 245 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;

# Column Regions by Pier
   region 560 -eleRange 111 114 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
   region 561 -eleRange 121 124 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
   region 562 -eleRange 131 134 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
   region 563 -eleRange 141 144 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;
   region 564 -eleRange 151 154 -rayleigh 0.0 $betaKcurr $betaKinit_mod $betaKcomm;


   region 1 -node  10126 9123 10127 9122 -rayleigh $alphaM 0.0 0.0 0.0; # assign mass proportional damping to structure (assign to nodes with mass)
   region 2 -node  10136 9133 10137 9132 -rayleigh $alphaM 0.0 0.0 0.0;
   region 3 -node  10146 9143 10147 9142 -rayleigh $alphaM 0.0 0.0 0.0;
   region 4 -node  10156 9153 10157 9152 -rayleigh $alphaM 0.0 0.0 0.0;

   region 8 -node  10226 9223 10227 9222 -rayleigh $alphaM 0.0 0.0 0.0;
   region 9 -node  10236 9233 10237 9232 -rayleigh $alphaM 0.0 0.0 0.0;
   region 10 -node 10246 9243 10247 9242 -rayleigh $alphaM 0.0 0.0 0.0;
   region 11 -node 10256 9253 10257 9252 -rayleigh $alphaM 0.0 0.0 0.0;
```

```

  region 15 -node 10326 9323 10327 9322 -rayleigh $alphaM 0.0 0.0 0.0;
  region 16 -node 10336 9333 10337 9332 -rayleigh $alphaM 0.0 0.0 0.0;
  region 17 -node 10346 9343 10347 9342 -rayleigh $alphaM 0.0 0.0 0.0;
  region 18 -node 10356 9353 10357 9352 -rayleigh $alphaM 0.0 0.0 0.0;

  region 21 -node 10426 9423 10427 9422 -rayleigh $alphaM 0.0 0.0 0.0;
  region 22 -node 10436 9433 10437 9432 -rayleigh $alphaM 0.0 0.0 0.0;
  region 23 -node 10446 9443 10447 9442 -rayleigh $alphaM 0.0 0.0 0.0;
  region 24 -node 10456 9453 10457 9452 -rayleigh $alphaM 0.0 0.0 0.0;

  region 27 -node 10526 9523 10527 9522 -rayleigh $alphaM 0.0 0.0 0.0;
  region 28 -node 10536 9533 10537 9532 -rayleigh $alphaM 0.0 0.0 0.0;
  region 29 -node 10546 9543 10547 9542 -rayleigh $alphaM 0.0 0.0 0.0;
  region 30 -node 10556 9553 10557 9552 -rayleigh $alphaM 0.0 0.0 0.0;


###################################################################
### DEFINE ANALYSIS OPTIONS, NEEDED LISTS OF STUFF TO RECORD, ETC.
# Define control nodes for monotonic and cyclic pushover - at top of leaning column
     set poControlNodeNum            15
     set poControlNodeNumCyclic      15

# Define a list of element numbers to record - record the columns or primary frame and leaning column - these are used for computing base shear and story shear
    set elementNumToRecordLIST { 111 121    112 122    113 123   114 124    }

# Define a list of joint numbers to record - all joints of primary frame
    set jointNumToRecordLIST {}

# Define a list of node numbers to record - top/bottom node of joint in left column of each floor, leaning column nodes, base spring nodes
    set nodeNumToRecordLIST { 126 226  10126 10226  11 12 13 14 15    31 32 33 34 35 }
  set springnodeNumToRecordLIST { 116 126  216 226   316 326   416 426   516 526 }
# Define a list of hinge elements to record - these are the springs at the base of the columns (elastic foundation + column PH)
    set hingeElementsToRecordLIST  {}

# Define a list of column numbers at the base of the frame (including the leaning column); this is for base shear calculations
    set columnNumsAtBaseLIST { 111 121 131 141 151}

# Define a list of column numbers at each story (including the leaning column); this is for story shear calculations
    set columnNumsAtEachStoryLIST { { 111 121 131 141 151 }
    { 112 122 132 142 152 }
    { 113 123 133 143 153 }
    { 114 124 134 144 154 }}

######################## Start Panos ##########################

  set zerolengthelementNumToRecordLIST  { { 3112 3212 3312 3412 3512 }
    { 3122 3222 3322 3422 3522 }
    { 3132 3232 3332 3432 3532 }
    { 3142 3242 3342 3442 3542 }}

######################## End Panos ############################

# Define a list of heights of each floor (for computing story drifts)
    set floorHeightsLIST { 0 144 288 432 576}

# Define a list of the node numbers at each floor (always use node 3 of the joint because it is at the slab level and we measure all height to there)
    set nodeNumsAtEachFloorLIST {-1  12 13 14 15}

######################## Start Panos ##########################

  set nodeNums1stFloorSpringsLIST {12 22 32 42 52};
  set nodeNums2ndFloorSpringsLIST {13 23 33 43 53};
```

```
  set nodeNums3rdFloorSpringsLIST {14 24 34 44 54};
  set nodeNums4thFloorSpringsLIST {15 25 35 45 55};

  set springnodeNums1stFloorSpringsLIST {126 226 326 426 526};
  set springnodeNums2ndFloorSpringsLIST {136 236 336 436 536};
  set springnodeNums3rdFloorSpringsLIST {146 246 346 446 546};
  set springnodeNums4thFloorSpringsLIST {156 256 356 456 556};

######################## End Panos ##########################
##############################################################
#### START NRS

  set columnRhoLIST { {  0.00102  0.00102  0.00102  0.00102  0.00102 }
    {  0.00102  0.00102  0.00102  0.00102  0.00102 }
    {  0.00102  0.00102  0.00102  0.00102  0.00102 }
    {  0.00102  0.00102  0.00102  0.00102  0.00102 }}

  set columnFswLIST { { 17. 17. 17. 17. 17.}
    { 17. 17. 17. 17. 17.}
    { 17. 17. 17. 17. 17.}
    { 17. 17. 17. 17. 17.}}

  set columnWidthLIST { { 18. 18. 18. 18. 18.}
     { 18. 18. 18. 18. 18.}
     { 18. 18. 18. 18. 18.}
     { 18. 18. 18. 18. 18.} }

  set columnDepthLIST { { 15.5 15.5 15.5 15.5 15.5}
     { 15.5 15.5 15.5 15.5 15.5}
     { 15.5 15.5 15.5 15.5 15.5}
     { 15.5 15.5 15.5 15.5 15.5}}

  set fpc_NRS 4000.
#### END NRS
##############################################################
```