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Impact of Large Gravity Loads on Buckling Restrained Braced Frame Performance

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Impact of Large Gravity Loads on Buckling

Restrained Brace Frame Performance

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

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The Buckling Restrained Braced Frame (BRBF) is used in steel structures as a lateral load resisting system for seismic events. In typical design procedure the impact of gravity loads acting on BRBFs is neglected and the beams and columns of the structure are designed to resist all gravity loads. In actuality BRBFs are supporting portions of gravity loads acting on the structure which may be changing the overall performance of BRBFs.

The purpose of this study is to determine the impact of large gravity loads on BRBF performance. This is done using finite element analysis to test two different structures supporting large gravity loads. The first structure is a seven story structure consisting of different BRBF configurations; the second structure is a three story structure with all BRBFs in an eccentrically braced configuration.

Each structure was modeled with applied ground motion simulations with and without gravity loads, and with gravity loads but no applied ground motion simulations. Results indicate that gravity loads have no significant impact on the overall performance of BRBFs for either structure.

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1 Introduction

A Buckling Restrained Braced Frame (BRBF) is a special class of the Concentrically Braced Frame (CBF) and is growing more popular in the United States as an alternative to the conventional steel braced frame because it does not buckle when in compression and exhibits stable hysteretic behavior. With an increasing use of BRBFs there is further need for research and validation of current design procedures. This thesis discusses the impact of large gravity loads on the performance of BRBFs.

1.1 Buckling Restrained Brace

A Buckling Restrained Brace (BRB) consists of a steel core, coated with an unbonding material, which is surrounded by a concrete mortar encased in a steel tube (see Figure 1-1). The steel core is the only component of the brace that resists applied axial forces, the specialized mortar and steel tube act as a buckling restraining mechanism inhibiting the steel core from buckling when in compression. The BRB dissipates axial forces through tension and compression yield cycles (see Figure 1-2) leaving the remaining components of the structure such as beams and columns elastic. Since the brace does not buckle, ductility and dissipation are increased, and story drift and damage to structural and non-structural building materials are reduced creating a more economical design (AISC 2006).

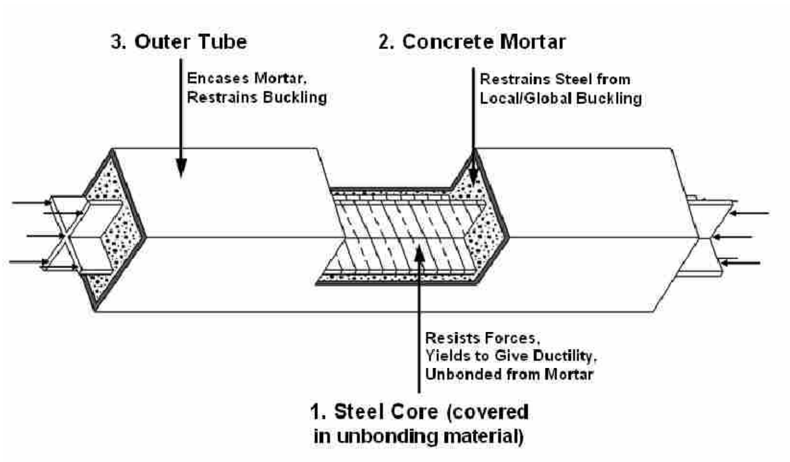

Figure 1-1 Buckling restrained brace schematic (Coy, 2007)

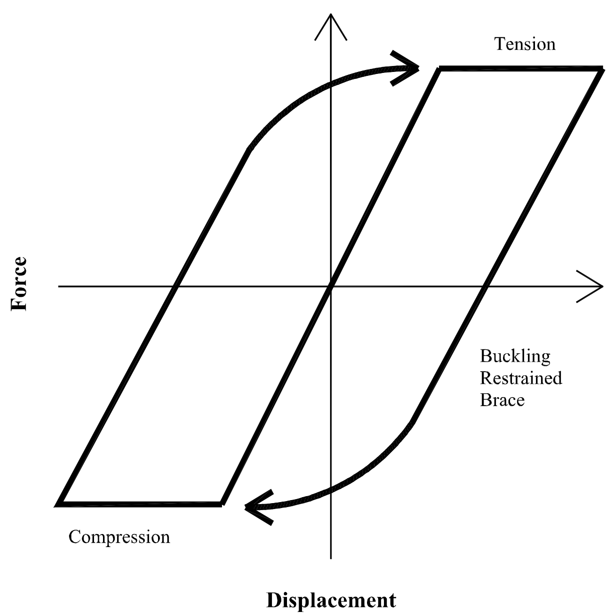

Figure 1-2 Buckling restrained brace hysteretic behavior

1.2 BRBF Experimental Analysis

Some of the first tests done on BRBFs were performed by Watanabe et al. (1988). They discovered that BRBs won't buckle if the buckling load of the steel tube is greater than the yielding load working on the core member. BRBs display stable hysteretic behaviors even after the yielding of the core member and possibly even during extensive deformation of the frame.

To understand the subassembly behavior of BRBFs, Aiken et al. (2002), conducted the first large-scale BRBF laboratory test in the United States. They determined that rotations at the ends of the BRBs had no negative influence on their behavior; hysteretic behaviors of the BRB were not influenced by combined axial and flexural demands, and orientation of the core plate, either vertically or horizontally, had no influence on the BRB hysteretic behavior.

Another set of large-scale tests was conducted by Fahnestock et al. (2007) using improved BRB connections to determine if BRBs reach full ductility capacity when installed in frames. They determined that good performance in the connection regions and BRBs resulted from pinned connections and end collars with stocky gusset plates. With adequate connection improvements they observed excellent performance for BRBFs designed using the current code-based equivalent-lateral force procedure.

Black et al. (2003) developed a mathematical model of a BRB and used experimental results to validate the model. Then they determined which mode of BRB instability was most critical. By using the Bouc-Wen hysteretic model they were able to match the experimental behavior of the BRB accurately. They discovered that the plastic torsional buckling of the BRB inner core was the most critical mode of instability.

Hussain et al. (2006) performed a case study on a project in Los Angeles to understand the cost comparison between structures designed with BRBFs and with CBFs. They determined that the overall cost of a structure designed with BRBFs was essentially the same as those designed with CBFs; however, structures designed with BRBFs were potentially more cost effective because they experience less structural damage after a seismic event.

Roder et al. (2006) conducted an experiment representing conditions in a real braced frame structure. The objectives were to verify current design standards for BRBFs and determine possible ways to improve the gusset plate connection. They observed that the BRBs exhibited excellent hysteretic behavior with good energy dissipation; the frame deformation capacity however was limited by the gusset plate connection. Tapered gusset plates performed better than rectangular gusset plates and there was no difference in response if the bolt connection was designed as slip critical or as bearing bolts.

Takeuchi et al. (2008) examined past experiments of BRBs to determine if there were relationships between the cumulative deformation capacity and the applied loading history. They determined that at larger plastic strains the accuracy of Miner's method for estimating decreases. They proposed a new method for estimating the cumulative deformation capacity of BRBs under random amplitudes; the method is easier to use because it does not require the calculation of individual amplitudes, which is accomplished by separating the hysteretic loop into the skeleton part and the Bauschinger part.

1.3 BRBF Computer Simulations

Since experimental studies of BRBFs can be expensive and time consuming, many BRBF studies are now being performed analytically using computer methods such as Finite Element Modeling (FEM). Sabelli et al. (2003) studied the seismic response of 3 and 6 story buildings designed with BRBs. They concluded that BRBs are a better alternative to overcome the problems with Special Concentric Braces (SCBs), such as unsymmetrical properties in tension and compression and limited ductility and energy dissipation under cyclic loading. For the cases studied they observed that varying the R factor between 6 and 8 had no effect on the average maximum inter-story drift.

Kim and Choi (2004) used 5, 10, and 20 story computer models to investigate the energy dissipation capacity and earthquake response of steel structures designed with BRBs as the lateral force resisting system. They observed that as the stiffness of BRBs increased, the maximum displacements of the structures generally decreased, and they determined that the best way to achieve desired BRB stiffness was to vary the cross-sectional area of the BRB as opposed to changing its yield stress.

Asgarian and Amirhesari (2008) conducted nonlinear dynamic analysis to determine the effects of strength and stiffness degradation of an Ordinary Brace Frame (OBF) and BRBF. They observed that Ordinary Brace (OB) members lost significant strength and stiffness in the post buckling region while the BRB maintained its strength and stiffness since no buckling occurred. In general BRBs story shears were greater than those of OBs; however, story drifts for BRBs were less than those for OBs. They concluded that BRBs performed better than OBFs.

1.4 Typical Design Convention for BRBFs

Like the Special Concentrically Braced Frame (SCBF), a BRBF is designed for significant inelastic deformations when resisting the axial forces caused by a seismic event. The cross-sectional area of the steel core is designed to resist all axial loads and yield close to the demand calculated from the applicable building code. In the typical design procedure, columns and beams are designed assuming that the BRBs will not support any dead and live loads. Since BRBs are expected to yield and be damaged in a seismic event, the beams and columns are designed neglecting the BRBs so the building will remain stable in case BRBs need to be removed and replaced. BRBs are designed neglecting the impact of any gravity loads, however, in reality, when BRBs are put into the structure gravity loads are transferred into the BRBs (AISC 2006).

1.5 Objective

The purpose of this research is to better understand the performance of BRBFs subject to large gravity loads and to develop possible recommendations for designing BRBFs under these circumstances. This will be done by generating and comparing the results of different computer models using a nonlinear dynamic analysis platform called Open System for Earthquake Engineering Simulation (OpenSees).

2 Configuration Effects of Brace Gravity Loads

The effects of gravity loads on a brace depend on the configuration of the frame and member properties. Consider the frame shown in Figure 2-1.

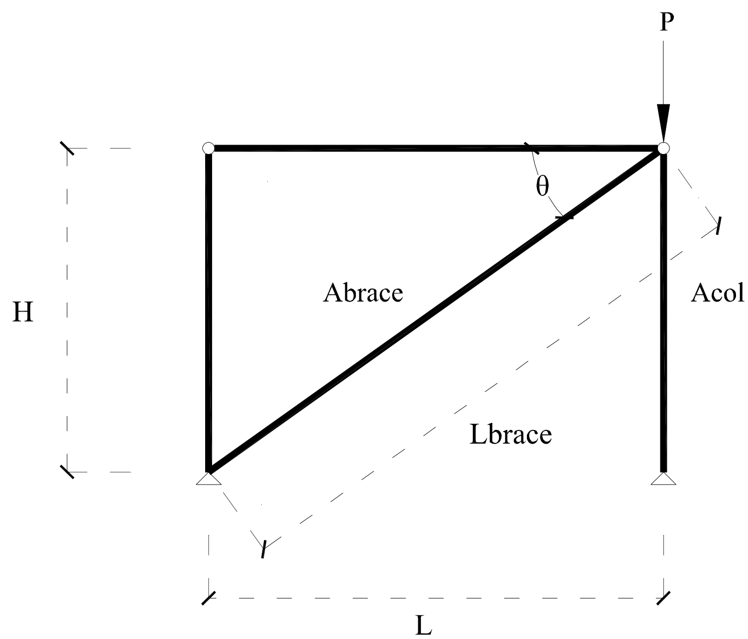

Figure 2-1 Typical braced frame

The brace supports gravity load based on its relative stiffness to that of the column. Equations 2-1 through 2-6 show how to compute brace and column stiffness and the brace force ratio according to different brace configurations.

$$Kcol = \frac{Acol * E}{H} \tag{2-1}$$

$$Kbrace = \frac{Abrace * E}{Lbrace} \tag{2-2}$$

$$KbraceVert = Kbrace * sin^2\theta \tag{2-3}$$

$$ColForce = P\left(\frac{Kcol}{Kcol + KbraceVert}\right) \tag{2-4}$$

$$BraceForceVert = P\left(\frac{KbraceVert}{KbraceVert + Kcol}\right) \tag{2-5}$$

$$BraceForceRatio = \left(\frac{BraceForceVert}{P}\right) \tag{2-6}$$

where *Acol* is the area of the column, *P* is the applied force, *E* is the modulus of elasticity of the material, *H* is the vertical height of the frame, and *Kcol* is the stiffness of the column. *Abrace* is the area of the brace, *Lbrace* is the length of the brace, and *Kbrace* is the stiffness of the brace. The angle, θ, is the angle between the beam and the brace and *KbraceVert* is the vertical stiffness of the brace. *ColForce* is the force acting on the column, *BraceForceVert* is the vertical force acting on the brace, and *BraceForceRatio* is the ratio of the vertical brace force divided by the total force resisted by the brace and column. Figure 2-2 shows the brace force ratio for different brace-column area ratios and different brace angles.

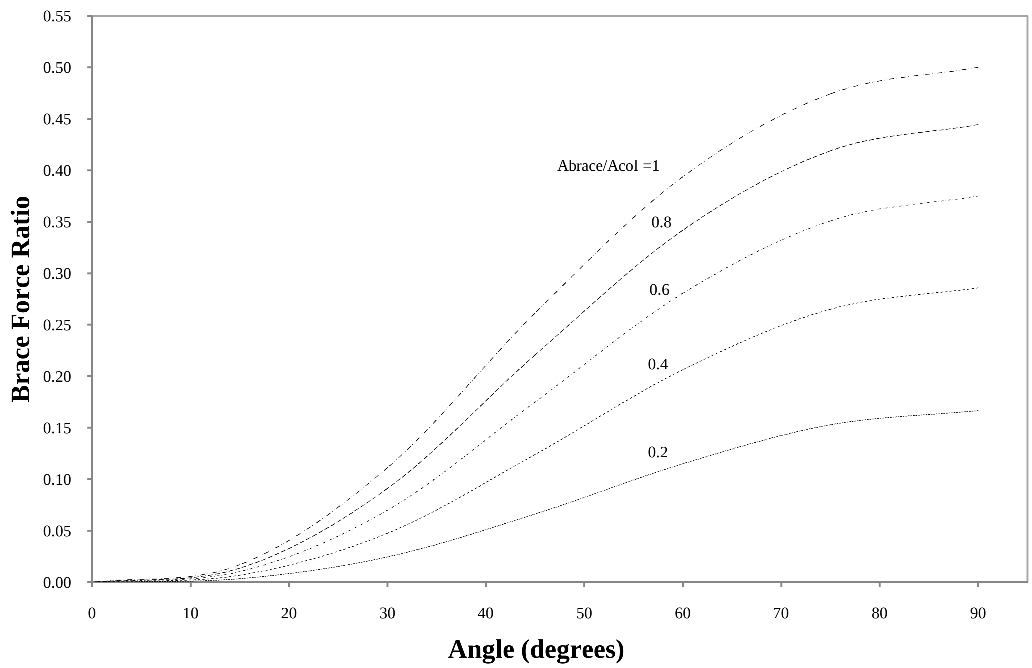

Figure 2-2 Brace force ratio for typical braced frame

Considering a brace with area equal to that of the column, same material properties as the column, and an angle, θ, of 90°, would result in a brace vertically aligned with the column; the brace force ratio would therefore be 0.5. Considering now a more typical brace-column area ratio in the range of 0.20 to 0.40, a brace with the same material properties as the column, and a more typical brace angle in the range of 30 to 60°, the brace force ratio would be in the range of 0.02 to 0.21. This indicates that even though gravity loads are neglected in brace design in actuality the brace is supporting a certain ratio of the gravity loads.

Consider the chevron frame shown in Figure 2-3. The braces support gravity load based on their relative stiffness to that of the beam. Equations 2-7 through 2-10 show how to compute beam and brace stiffness and the brace force ratio according to different brace configurations.

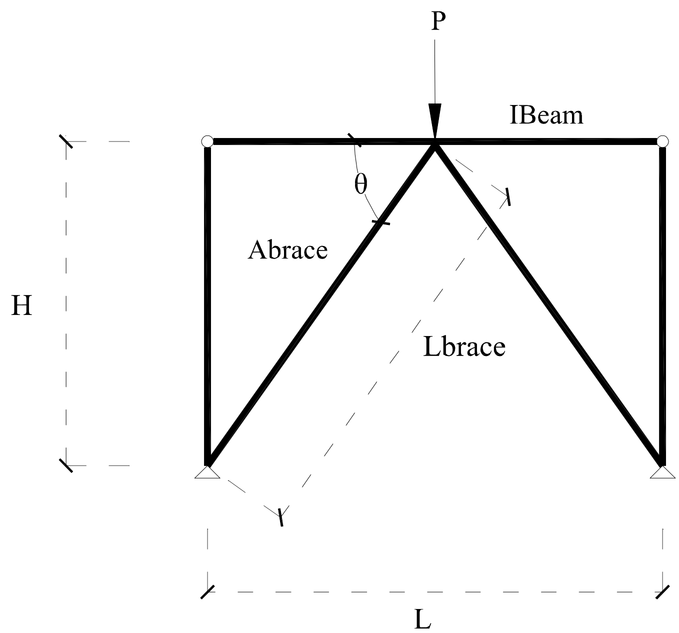

Figure 2-3 Chevron bracing

$$Kbeam = \frac{48 * E * Ibeam}{L^3} \quad \text{(2-7)}$$

$$KbraceVert = 2 * Kbrace * \sin^2\theta \quad \text{(2-8)}$$

$$BraceForceVert = P\left(\frac{KbraceVert}{KbraceVert + Kbeam}\right) \quad \text{(2-9)}$$

$$BraceForceRatio = \left(\frac{BraceForceVert}{P}\right) \quad \text{(2-10)}$$

where *Ibeam* is the moment of inertia of the beam and *Kbeam* is the stiffness of the beam. *Kbrace* is the same as Equation 2-2; however, *Lbrace* is changed to the length of the brace as shown in Figure 2-3. Figure 2-4 shows the brace force ratio for different brace area-beam moment of inertia ratios and different brace angles.

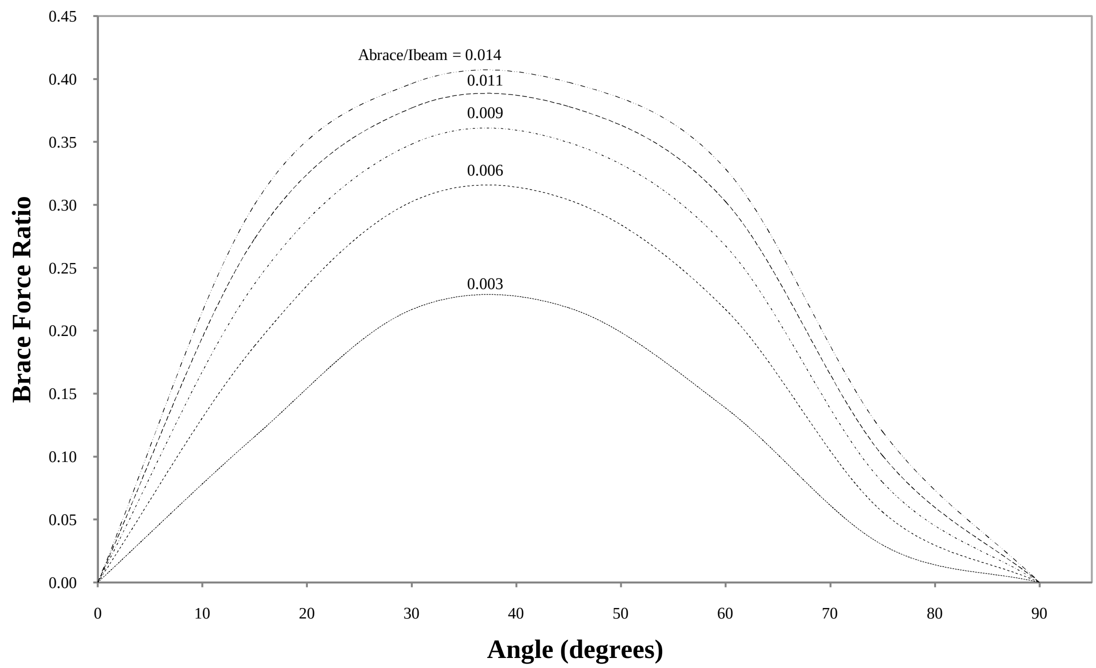

Figure 2-4 Brace force ratio for chevron bracing

Considering a typical brace area-beam moment of inertia ratio in the range of 0.003 to 0.006, a brace with the same material properties as the beam, and a typical brace angle in the range of 30 to 60°, the brace force ratio would be in the range of 0.14 to 0.32. Again this indicates that even though gravity loads are neglected in brace design in actuality the braces are supporting a certain ratio of the gravity loads.

3 Computer Analysis

To determine the impact of large gravity loads on BRBFs, two different frames of two different structures were analyzed using two-dimensional models in the nonlinear dynamic analysis platform OpenSees. The first model, Model 1, consists of a multi-bay seven story frame with varying story heights, beam spans, and BRB spans. Three different versions of Model 1 were generated for comparison purposes. Model 1.1 has applied ground motion simulations but no applied gravity loads, Model 1.2 has applied ground motion simulations and gravity loads, and Model 1.3 has applied gravity loads but no ground motion simulations.

The second model, Model 2, is a three bay three story frame consisting of BRBFs that are offset from the columns to create a BRBF in an eccentrically braced configuration. This system is used to offer more architectural advantages throughout the structure. The configuration of using a BRBF in an eccentrically braced configuration is new and not currently in the recommended design procedures; however, the design procedure used for this model is similar to that of an Eccentrically Braced Frame (EBF). Three different versions of the model were also generated for comparison purposes, Model 2.1 through Model 2.3, and are similar to Model 1.1 through Model 1.3.

3.1 Model 1

The frame which represents Model 1 is part of the Echelon Place Convention Center located in Las Vegas, Nevada. The 1,000,000 plus sq ft convention center is part of a multibillion-dollar project called Echelon Place which also consists of hotels, casinos, restaurants, and Las Vegas ExpoCenter. The convention center and other projects have been partially built but are currently on hold until further financing is obtained. This structure was selected for analysis because of the higher than usual axial loads in the frames and curiosity of the BRB manufacturer.

The frame used in Model 1 is located in the northern part of the convention center and is one of two major frames resisting axial loads in the east to west direction. A plan view of the building showing the BRBFs of interest is shown in Figure 3-1.

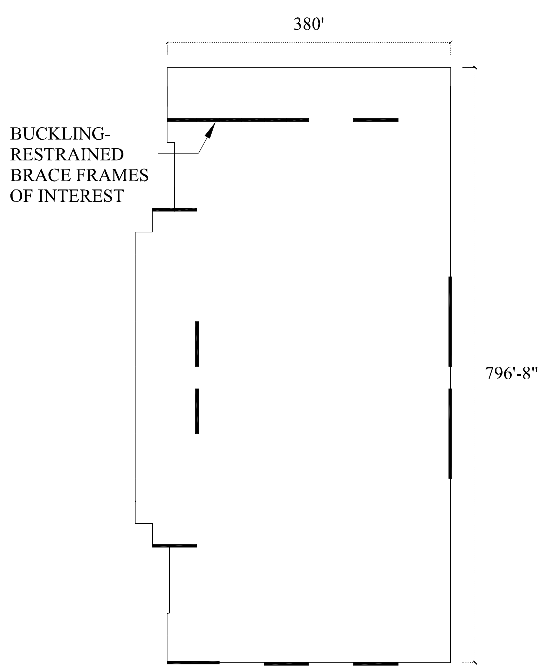

Figure 3-1 Plan view of structure with BRBFs of interest

Story elevations vary from 8 to 35.75 ft for a total structure elevation of 155.38 ft; the first bay length is 40 ft with remaining bays at 30 ft for a total length of 190 ft, and BRB lengths vary from 17 to 53.65 ft (see Figure 3-2). The member sizes of the beams, columns, box columns, and BRBs used in the model were those in the design plans of the structure (see Figure 3-3, Figure 3-4, and Table 3-1).

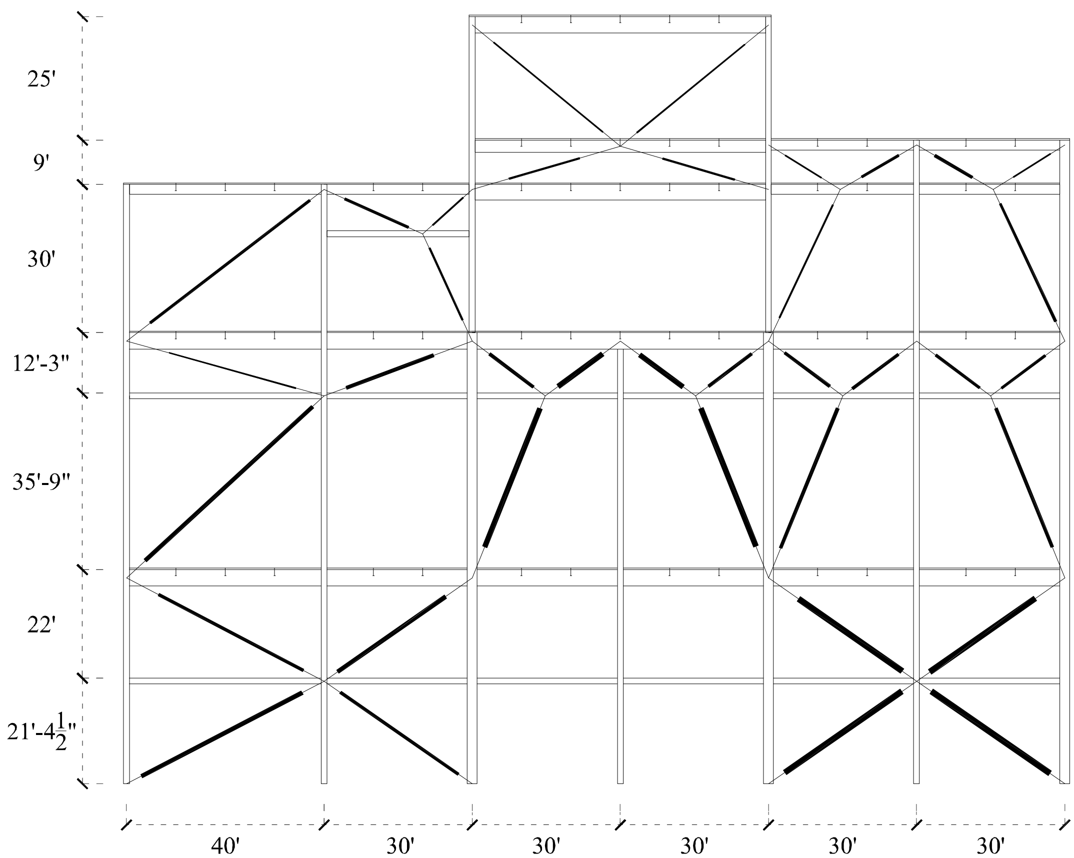

Figure 3-2 Elevation view of BRBFs of interest for Model 1

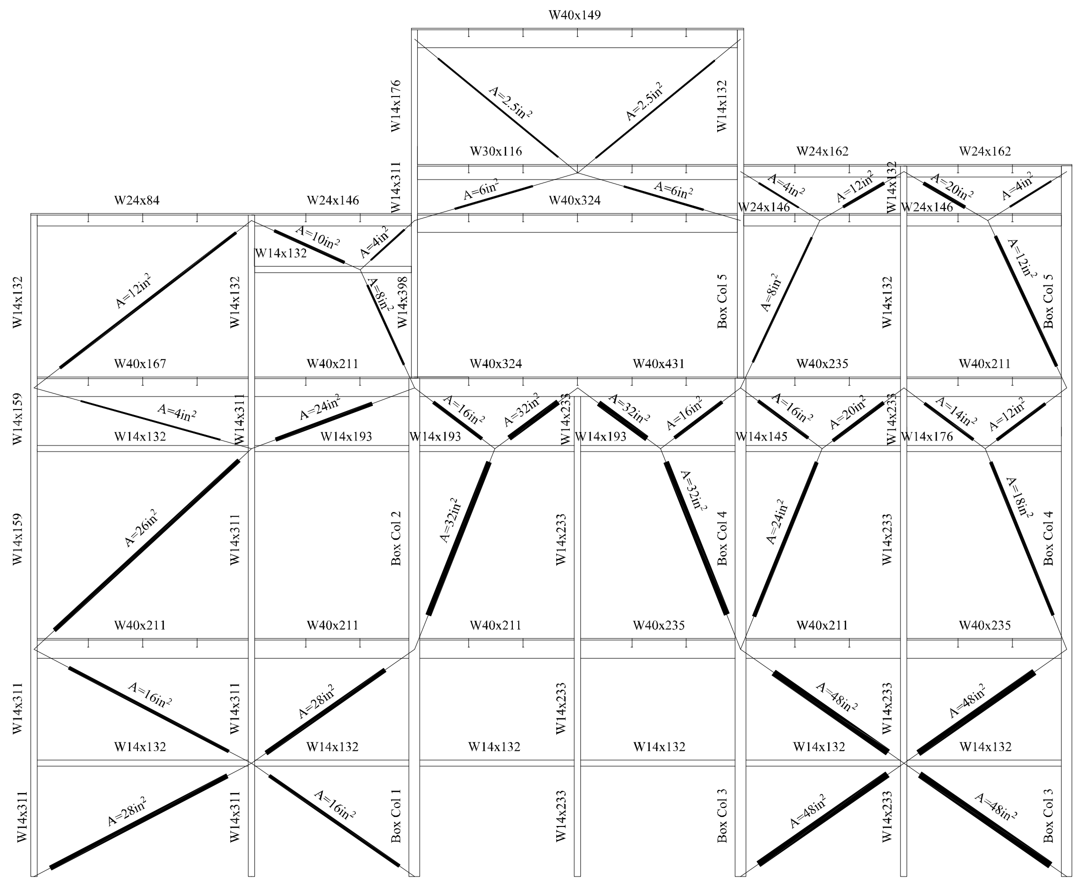

Figure 3-3 Elevation view and member details

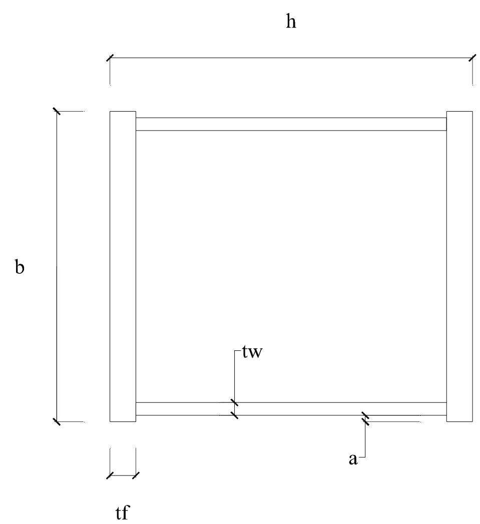

Figure 3-4 Box column variables

Table 3-1 Box column dimensions

Box Col	a (in)	b (in)	tf (in)	h (in)	tw (in)
1	0.50	24	2.25	24.50	2
2	0.50	24	2.25	24.50	1
3	0.50	24	3	26	2
4	0.50	24	2.25	24.50	1.50
5	0.50	24	2.25	24.50	1

3.2 Seismic Loads for Model 1

The seismic weights used for Model 1 were determined from concrete floor slabs, roof decking, miscellaneous materials, and exterior walls. The concrete floor slab depth is 7 inches, the roof decking depth is 3.5 inches, and the exterior wall width is 1 ft. The weight of concrete is 150 pcf for floor slabs, the roof decking weight was determined from standard roof decking catalogues to be 5 psf, the miscellaneous materials were assumed to be 10 psf, and the exterior walls were assumed to be 20 psf.

Since the locations of the lateral resisting frames are not symmetrical, the seismic weight of the entire structure was calculated and then divided according to individual frame stiffness. The seismic weights applied to the two-dimensional model frame were determined by calculating the stiffness ratio of each BRB in comparison to the stiffness of all BRBs at the same story level; that ratio was then multiplied by the total seismic weight of each story level and applied as a point load to the corresponding BRB. The total seismic weight of the structure was approximately 157,000 kips and the total seismic weight applied to the frame was approximately 65,000 kips.

3.3 Gravity Loads for Model 1

Gravity loads for the main floors were determined using an unreduced 100 psf live load and 75 psf floor and 10 psf miscellaneous for dead load. Gravity loads for the roof were determined using an unreduced 20 psf live load and 5 psf roof deck and 10 psf miscellaneous for dead load. Gravity loads were factored using the LRFD factored combination 5 (AISC, 2005) (see Equation 3-1) and applied as point loads according to the corresponding tributary area of each column.

$$1.2D \pm 1.0E + 0.5L + 0.2S \qquad \textbf{(3-1)}$$

3.4 Ground Motion Simulations for Model 1

For the study of Model 1 eight different ground motions were scaled to have a 2% in 50 years hazard level. The design spectrum (see Figure 3-5) used for this model was calculated using SDS as 0.424 and SD1 as 0.183 based on the Las Vegas, Nevada construction site. The natural period of the structure was determined to be 1.85 seconds.

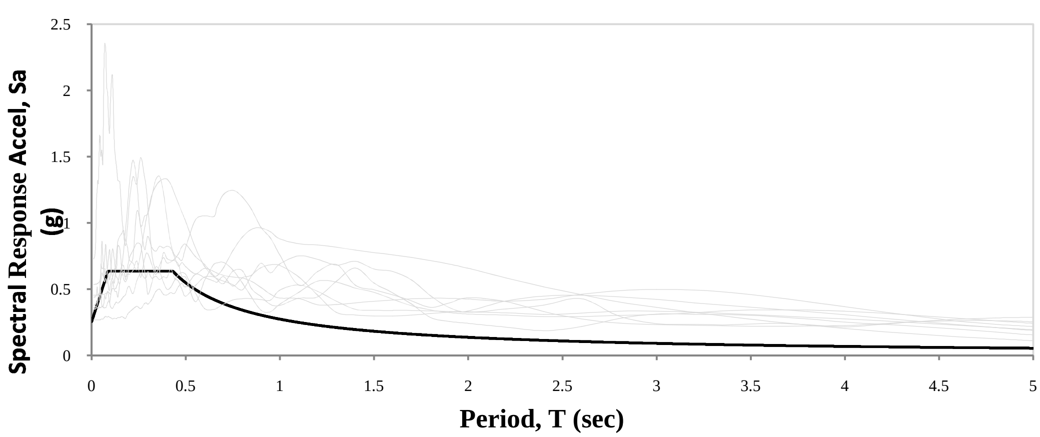

Figure 3-5 Design spectra and earthquake records used for Model 1

A second set of analyses were conducted with the scaled earthquakes multiplied by a factor of two to create larger demand forces and maximum story drifts for further investigation of the impact of large gravity loads on the BRBFs. Nonlinear analyses were performed to determine BRB force demand-capacity ratios, the average maximum story drifts, and BRB force-strain hysteresis.

3.5 Modeling of BRBs for Model 1

BRBs were modeled using corotational truss elements which allow the element to yield under axial forces. "The corotational formulation adopts a set of corotational axes which rotate with the element, thus taking into account an exact geometric transformation between local and global frames of reference" (Mazzoni, et al. 2006). The design variable for the BRB elements was the cross-sectional area taken from the design plans. All BRB elements were modeled using the Steel02 material object and were calibrated to produce hysteretic behavior consistent with BRBF test results from Coy (2007). The design yield stress of the BRBs used was 46 ksi.

Modeling of BRBs in FEM requires effective modeling procedures because of the special composition of the brace. The inner steel core cross-sectional area is larger on the outer portions of the brace and smaller in the middle so the middle portion of the brace will be the section that yields. In FEM modeling only one constant area is applied to a single element, advanced FEM modeling could include multiple small connected elements with varying areas; however for simplicity in BRB models, an effective modulus of elasticity, E_{eff}, is sufficient to compensate for the changing cross-sectional area of the brace. E_{eff} was calculated using Equations 3-2 through 3-4.

$$E_{eff} = E * \frac{L_1}{L_{BRB,Yield}} \tag{3-2}$$

$$L_{BRB,Yield} = 0.85\,(L_1 - 2L_2) \tag{3-3}$$

$$L_2 = \frac{d_{beam}}{sin\theta} + 24'' \tag{3-4}$$

where L_1 is the total brace length from centerline to centerline; the angle, θ, represents the slope of the brace across the bay and L_2 is the non-yielding length of the BRB. In Equation 3-4, the constant represents the gusset connection region which is stiff relative to the brace. Also $L_{BRB,Yield}$ was reduced by 15% to allow for a transition between non-yielding to yielding sections (Oxborrow, 2009). The variables listed are schematically shown in Figure 3-6.

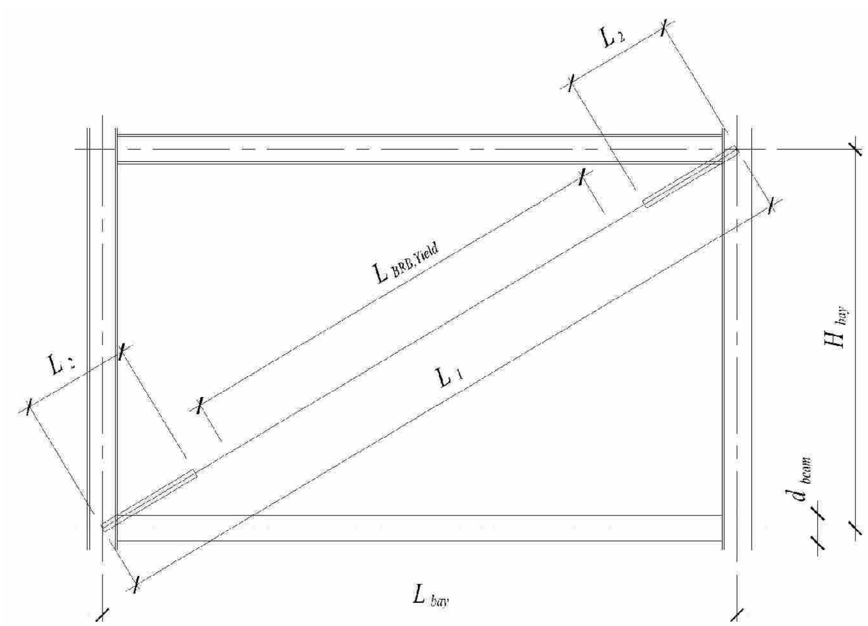

Figure 3-6 BRBF elevation view (Oxborrow, 2009)

3.6 Modeling of Beams, Columns, and Box Columns for Model 1

Beams, columns, and box columns were modeled using fiber w-sections and force-based nonlinear beam-column elements. Fiber sections were used to calculate flexural and axial stiffness by integrating strains across the section of each element. Box columns were modeled using uniaxial sections and force-based nonlinear beam-column elements. Elastic axial and inelastic flexural moment-curvature properties were individually defined at the section level. The material property used for all three was Steel02, a steel material using the Guiffre, Menegotto, and Pinto steel model with isotropic strain hardening, strain hardening values recommend by Mazzoni, et al. (2006) were used for this model. The design yield stress of beams, columns, and box columns used was 50 ksi.

3.7 Model 2 Configuration and General Details

Model techniques for Model 2 are very similar to Model 1. Five ground motions were used for this model and scaled to have a 10% in 50 years hazard level to be consistent with the original design of the structure. Story heights for Model 2 are 13 ft, bay lengths are 30 ft, and brace lengths are 29 ft (see Figure 3-7). The total seismic weight of the structure was approximately 6,500 kips and the total seismic weight applied to the frame was approximately 200 kips. The natural period of the structure was determined to be 0.71 seconds.

Gravity loads for the three levels of Model 2 were determined using an unreduced 50 psf live load and 75 psf floor and 10 psf miscellaneous for dead load. The tributary area used for gravity loads for the frames was 450 ft^2. Gravity loads were factored using the LRFD factored combination 5, (see Equation 3-1), and applied as tributary loads across the beams.

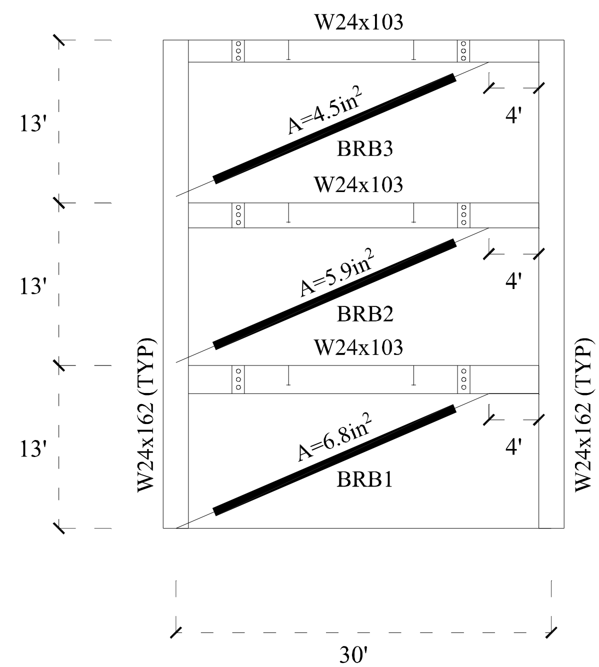

Figure 3-7 Elevation view of BRBFs of interest for Model 2

Subsequent sets of increased gravity loads were applied to the frame consisting of 2x, 4x, 8x, and 16x the original factored gravity loads for further analysis, only one ground motion simulation was used for these analyses. Because the frame is neither completely rigid nor completely flexible, two different versions of the frame were modeled with the increased gravity loads for comparison: a frame without a diaphragm and a frame with a rigid diaphragm constraint. The constraint of the frame with a rigid diaphragm is that columns of the same story level must have equal drift ratios.

4 Results

To evaluate the impact of large gravity loads on BRBF performance, results are compared for the different models. The results of interest are BRB force demand-capacity ratios, average maximum story drifts, and BRB force-strain hysteresis.

4.1 Model 1

4.1.1 BRB Force Demand-Capacity Ratio

The BRB force demand for each BRB of each model was determined from computer analyses. Eight ground motion simulations were performed and the average BRB demand force for each BRB was computed.

The BRB *force capacity* is the maximum force that a BRB can sustain before it starts to yield. The BRB force capacities were determined by taking the steel core cross-sectional area of each BRB and multiply it by its yield stress. The *BRB force demand-capacity ratio* is determined by dividing BRB force demand by the BRB force capacity; a ratio greater than one indicates that the BRB has exceeded its capacity and has yielded, however, ratios as high as two still may be reasonable due to the strain hardening of the material. The average BRB force demand-capacity ratios for the eight ground motion simulations were calculated.

The BRB with the highest average BRB force demand-capacity ratio from each story level of Model 1 with ground motion simulations scaled 2x was chosen for comparison of results (see Figure 4-1). It was observed that on most story levels several other BRBs were equal in value to the average BRB force demand-capacity ratio selected for comparison.

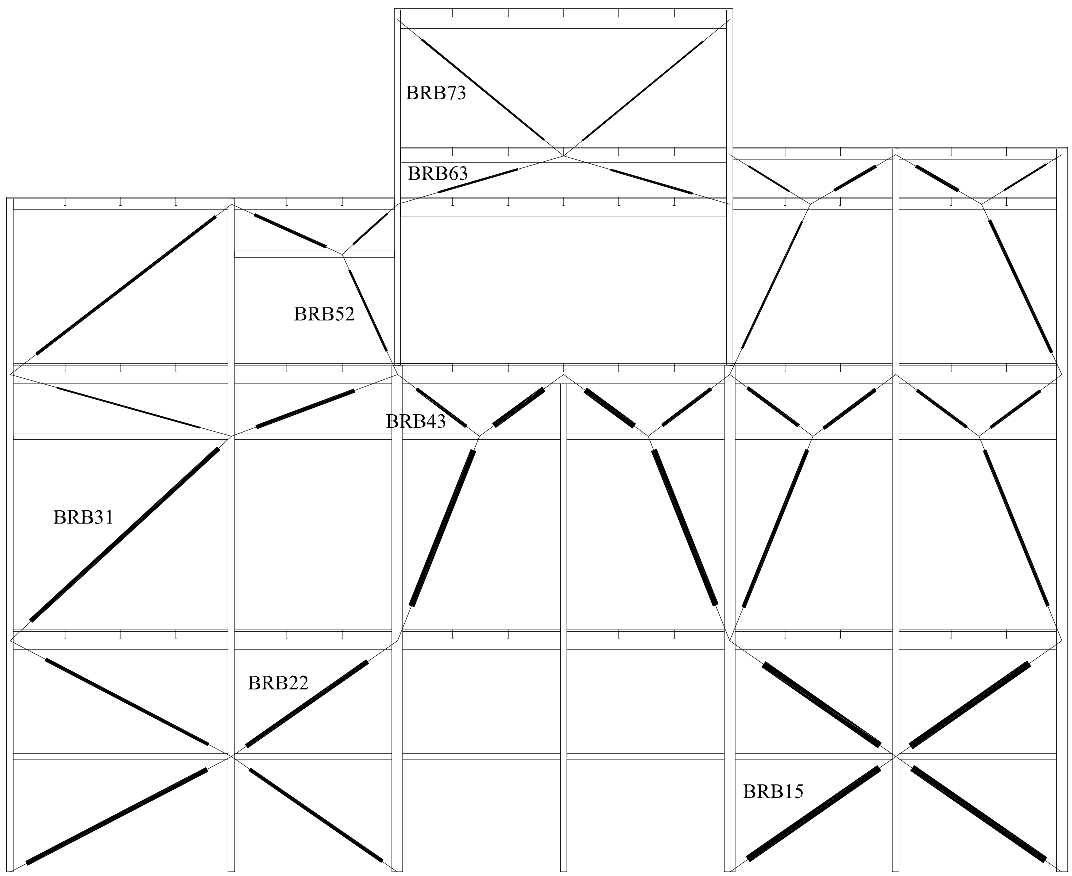

Figure 4-1 BRBs of interest for Model 1

The average BRB force demand-capacity ratio for the selected BRBs of the different models is shown in Table 4-1. The BRB force demand-capacity ratio for Model 1.1 and Model 1.2 are almost identical and show that some BRBs are yielding. The maximum BRB force demand-capacity ratio for both models is in member BRB52 with a BRB force demand-capacity ratio of 1.52, indicating significant yielding. In Model 1.3 the maximum BRB force demand-capacity ratio is 0.12 in member BRB43, indicating that BRBs are not yielding when resisting only gravity loads. Comparisons indicate that the presence of gravity loads had no significant impact on BRB force demand-capacity ratios.

Table 4-1 BRB force demand-capacity ratios for Model 1

BRB ID	1.1 Ground Motion No Gravity	1.2 Ground Motion With Gravity	1.3 No Ground Motion With Gravity
15	1.05	1.05	0.08
22	1.02	1.01	0.07
31	1.50	1.50	0.03
43	0.80	0.83	0.12
52	1.52	1.52	0.07
63	0.80	0.80	0.02
73	0.12	0.12	0.01

4.1.2 BRB Force Demand-Capacity Ratio for Ground Motion Simulations Scaled 2x

Ground motion simulations were scaled 2x for further comparison because several BRBs did not yield and the average maximum story drifts were relatively low. The average BRB force demand-capacity ratio for the ground motion simulations scaled 2x is shown in Table 4-2. The BRB force demand-capacity ratio for Model 1.1 and Model 1.2 are almost identical and some BRBs are yielding. The maximum BRB force demand-capacity ratio is in member BRB31 of Model 1.2 with a BRB force demand-capacity ratio of 1.89. Even with ground motion simulations scaled 2x, comparisons indicate that the presence of gravity loads had no significant impact on BRB force demand-capacity ratios.

Table 4-2 BRB force demand-capacity ratios for Model 1 for ground motion simulations scaled 2x

BRB ID	1.1 Ground Motion No Gravity	1.2 Ground Motion With Gravity	1.3 No Ground Motion With Gravity
15	1.55	1.55	0.08
22	1.50	1.50	0.07
31	1.88	1.89	0.03
43	1.16	1.17	0.12
52	1.72	1.72	0.07
63	1.13	1.13	0.02
73	0.16	0.16	0.01

4.1.3 Average Maximum Story Drift for Ground Motion Simulations

The average maximum story drifts for Model 1.1 and Model 1.2 are both shown in Figure 4-2. Story drifts represent the maximum story displacement divided by the story height. The average maximum story drifts for the eight ground motion simulations for Model 1.1 and Model 1.2 are almost identical. Figure 4-2 shows that the dashed line, which represents the model with gravity, overlaps the solid line, which represents the model without gravity; both have an average maximum story drift close to 0.01 radians. Comparisons indicate that the presence of gravity loads had no significant impact on the average maximum story drift.

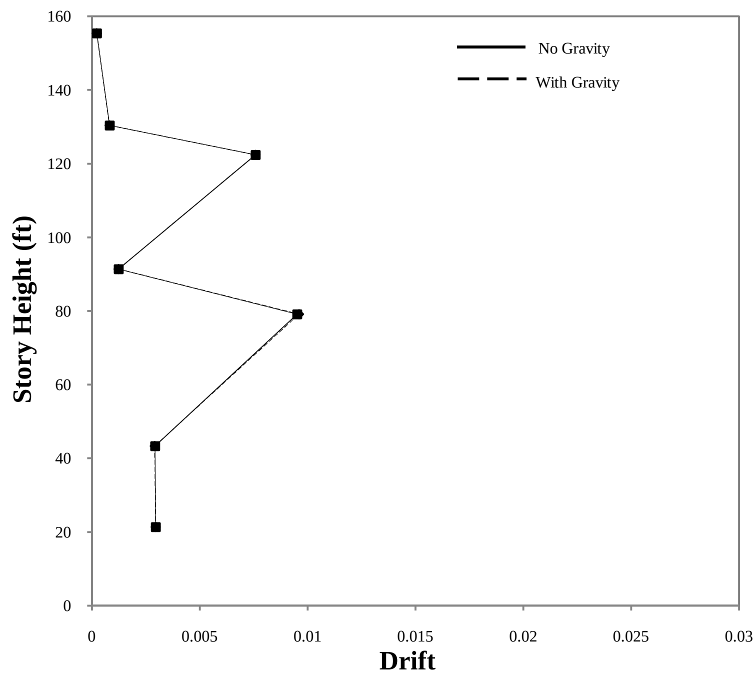

Figure 4-2 Average maximum story drift for Model 1.1 and Model 1.2

4.1.4 Average Maximum Story Drift for Ground Motion Simulations Scaled 2x

The average maximum story drifts for Model 1.1 and Model 1.2 for ground motion simulations scaled 2x are both shown in Figure 4-3. The average maximum story drifts for Model 1.1 and Model 1.2 again are almost identical; both have a maximum story drift close to 0.028 radians. Even with ground motion simulations scaled 2x, comparisons indicate that the presence of gravity loads had no significant impact on the average maximum story drift.

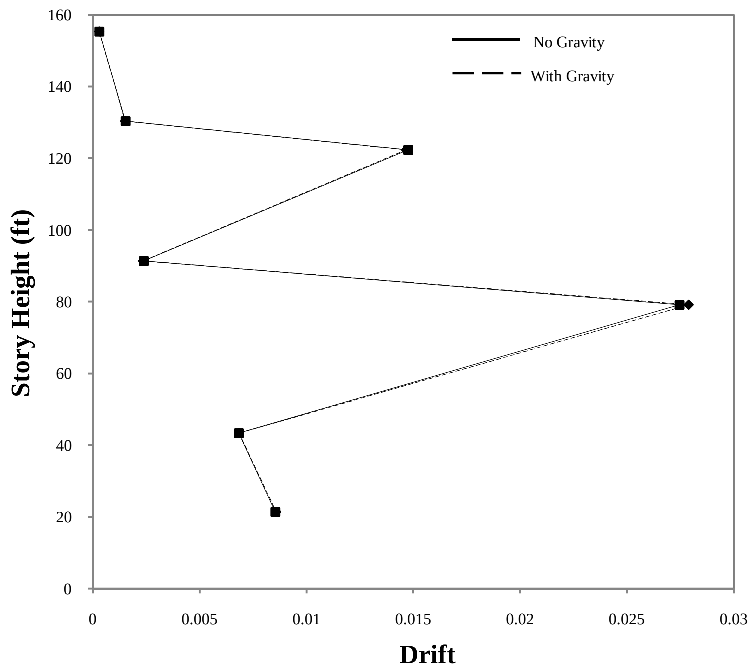

Figure 4-3 Average maximum story drift for Model 1.1 and Model 1.2 scaled 2x

4.1.5 Maximum Drift for Applied Gravity Loads with No Ground Motion Simulation

The maximum story drift for Model 1.3 was approximately zero. Almost no drift exists when only gravity loads are applied on the frame because it is mostly symmetrical and designed to resist much larger forces.

4.1.6 BRB Force-Strain Hysteresis

To check the BRB responses, BRB force-strain hysteresis were plotted and compared to BRB force capacity. Each hysteresis shows the history of the BRB force demand against BRB strain, or elongation of the BRB normalized according to BRB length and scaled for better comparison of the differing lengths. The plots of the BRB force-strain hysteresis for both ground motion simulation scales for Model 1.1 and Model 1.2 are shown in Figure 4-4 and Figure 4-5.

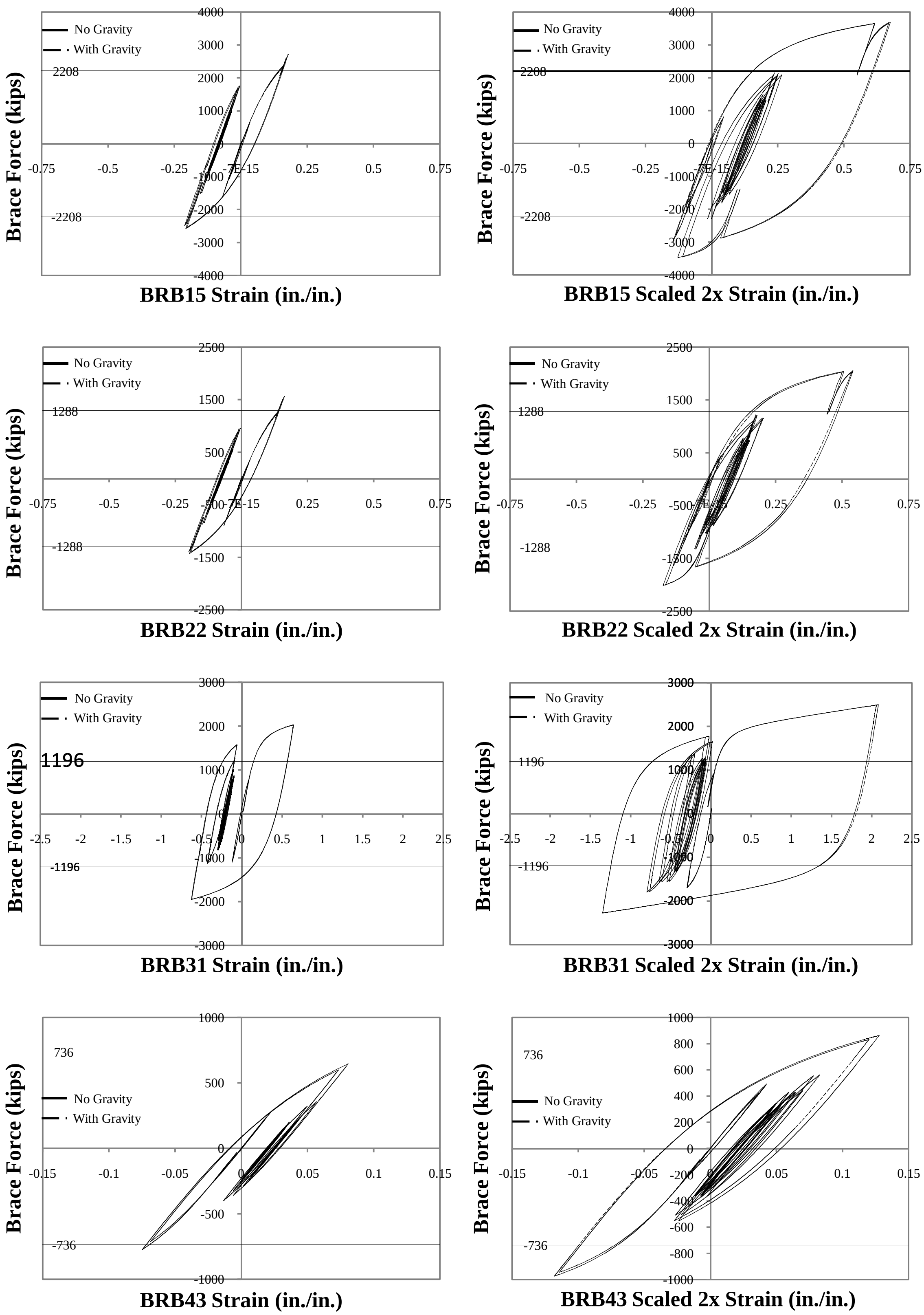

Figure 4-4 BRB force-strain hysteresis for Model 1.1 and Model 1.2

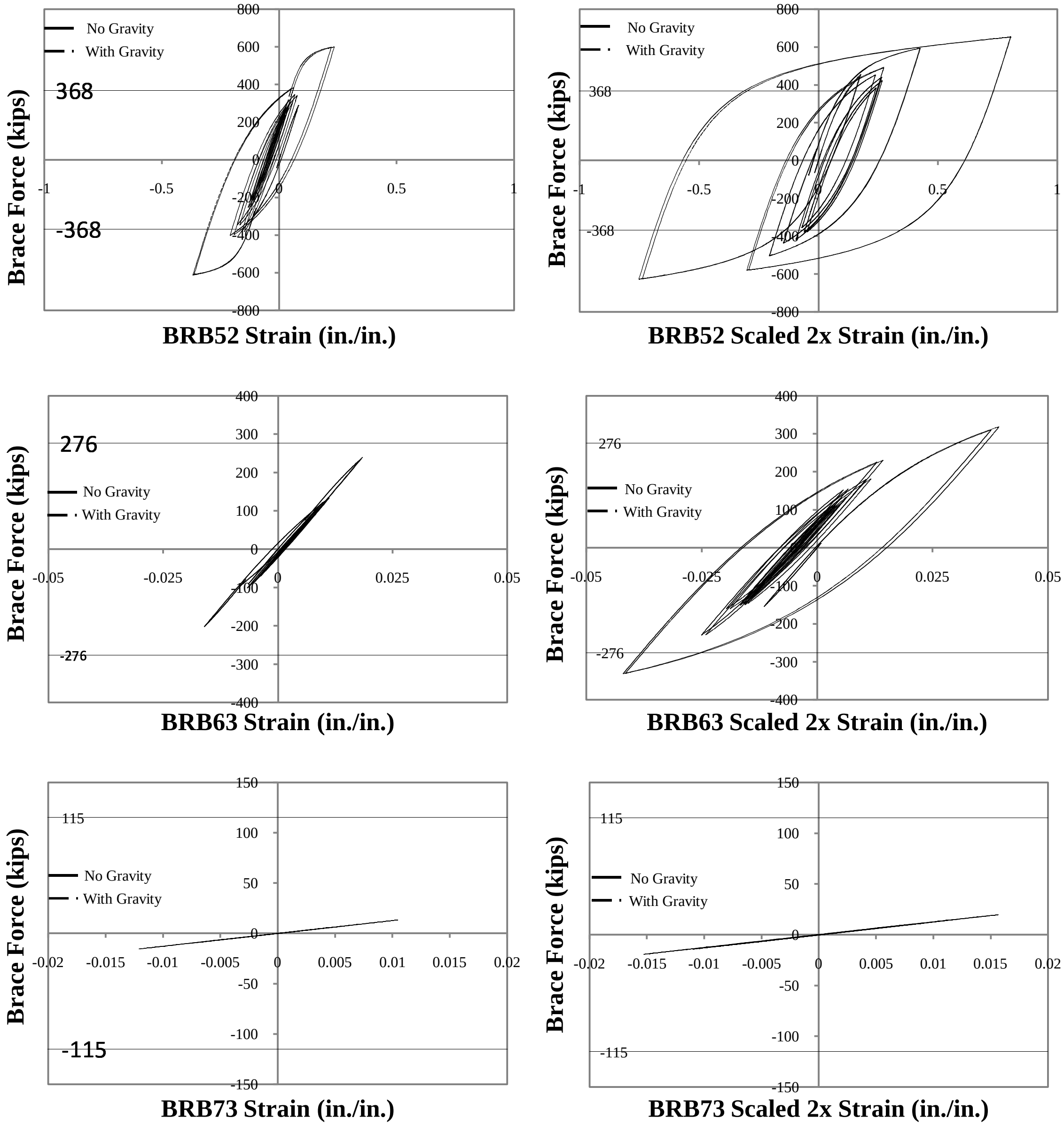

Figure 4-5 BRB force-strain hysteresis for Model 1.1 and Model 1.2 (continued)

The hysteresis show that yielding is occurring when the BRB force demand exceeds the BRB force capacity and no yielding occurs when the BRB force demand is less than the BRB force capacity. Comparisons indicate that the presence of gravity loads had no significant impact on BRB force-strain hysteresis.

4.2 Model 2

4.2.1 BRB Force Demand-Capacity Ratio

All BRBs from Model 2 were chosen for comparison of results (see Figure 4-6). The average BRB force demand-capacity ratios for the different models are shown in Table 4-3. The BRB force demand-capacity ratio for Model 2.1 and Model 2.2 are almost identical and show that some BRBs are yielding, the maximum BRB force demand-capacity ratio is in member BRB3 of Model 2.2 with a BRB force demand-capacity ratio of 1.67, indicating significant yielding. In Model 1.3 the maximum BRB force demand-capacity ratio is 0.05 in member BRB3, showing that BRBs are not yielding when resisting only gravity loads. Comparisons indicate that the presence of gravity loads had no significant impact on BRB force demand-capacity ratios.

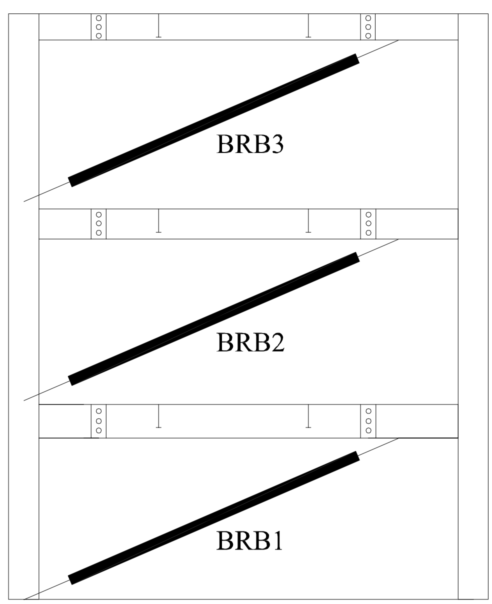

Figure 4-6 BRBs of interest for Model 2

Table 4-3 BRB force demand-capacity ratios for Model 2

BRB ID	2.1 Ground Motion No Gravity	2.2 Ground Motion With Gravity	2.3 No Ground Motion With Gravity
1	1.24	1.24	0.02
2	1.42	1.42	0.01
3	1.67	1.66	0.05

4.2.2 Average Maximum Story Drift for Ground Motion Simulations

The average maximum story drifts for Model 2.1 and Model 2.2 are both shown in Figure 4-7.

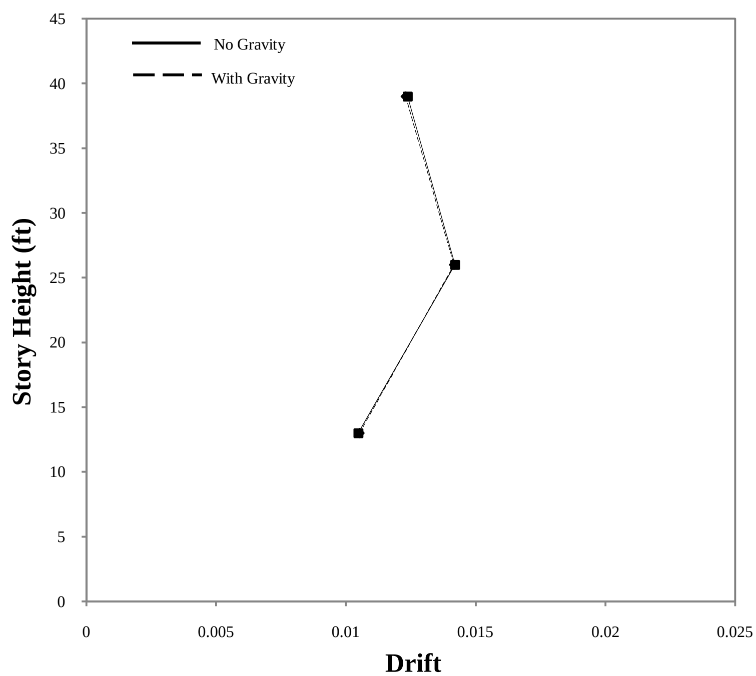

Figure 4-7 Average maximum story drift for Model 2.1 and Model 2.2

The average maximum story drifts for the five ground motion simulations for Model 2.1 and Model 2.2 are almost identical; both have an average maximum story drift close to 0.014 radians. Comparisons indicate that the presence of gravity loads had no significant impact on the average maximum story drift.

4.2.3 Maximum Drift for Applied Gravity Loads with No Ground Motion Simulation

The maximum story drift for Model 2.3 was approximately zero. Almost no drift exists when only gravity loads are applied on the frame because it is designed to resist much larger forces.

4.2.4 Increased Gravity Load Cases

The maximum story drifts for the subsequent sets of increased gravity loads applied to the frame at 2x, 4x, 8x, and 16x the original factored gravity loads are shown for the frame with no diaphragm in Figure 4-8 and frame with a rigid diaphragm constraint in Figure 4-9.

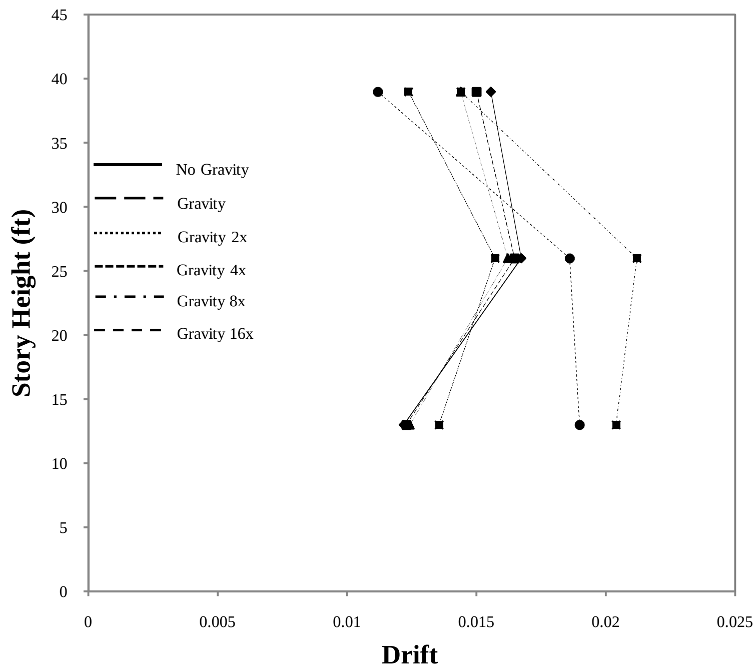

Figure 4-8 Maximum story drift for frame with no diaphragm

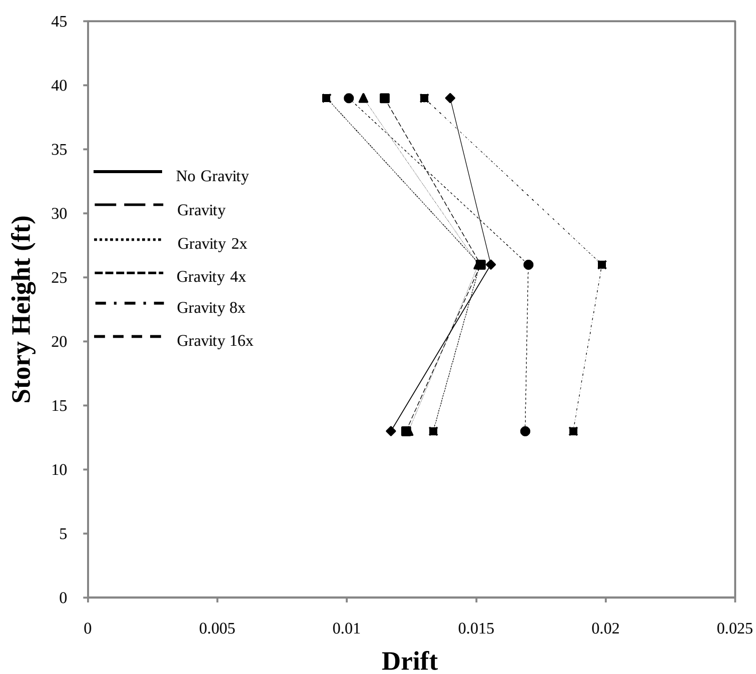

Figure 4-9 Maximum story drift for frame with a rigid diaphragm constraint

4.2.5 BRB Force-Deformation Hysteresis

The plots of the BRB force-deformation hysteresis are shown in Figure 4-10. Each hysteresis shows the history of the force demand on the BRB against the BRB deformation and BRB capacity; BRBs were not normalized since all BRBs have the same length. Comparisons indicate that the presence of gravity loads had no significant impact on BRB force-strain hysteresis.

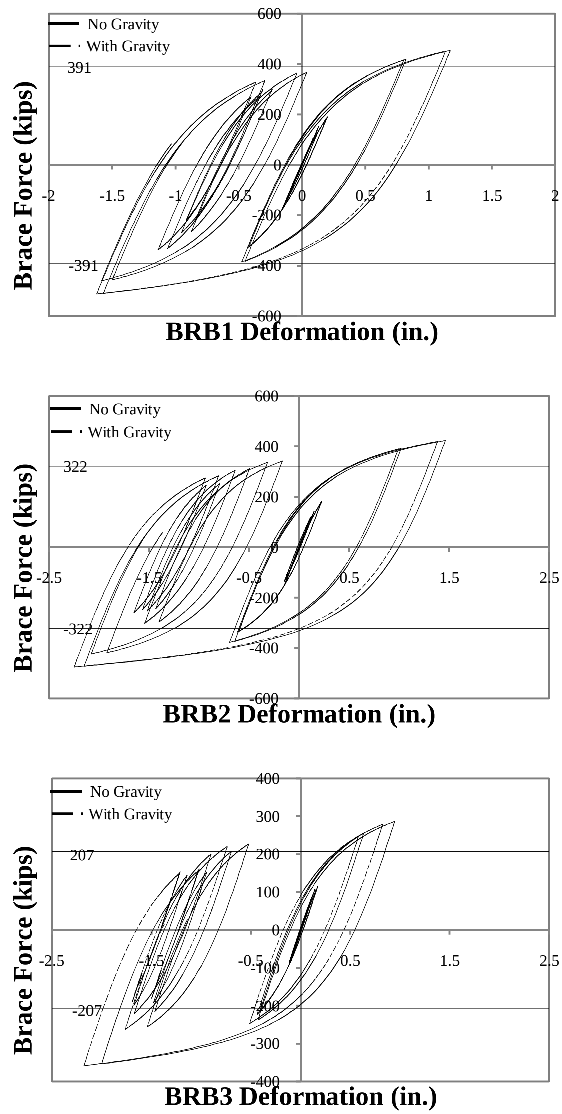

Figure 4-10 BRB force-deformation hysteresis for Model 2.1 and Model 2.2

5 Discussion and Conclusions

The purpose of this research is to draw conclusions and possible design recommendations for the impact of large gravity loads on BRBF performance. This was accomplished using a nonlinear finite element analysis to test two different structures with different versions of each model consisting of applied ground motion simulations and no applied gravity loads, with applied ground motion simulations and applied gravity loads, and with applied gravity loads and no applied ground motion simulations.

5.1 Summary of Results Found

Results from Model 1 and Model 2 with applied ground motion simulations and no applied gravity loads when compared to the models with applied ground motion simulations and applied gravity loads showed no significant difference in the BRB force demand-capacity ratio, average maximum story drift, BRB force-strain hysteresis, and BRB force-deformation hysteresis. The results of applied gravity loads and no applied ground motion simulations showed BRB force demand-capacity ratio to be low, maximum story drift approximately zero, force-strain and force-deformation values to be low. These results indicate that large gravity loads had no significant impact on BRBF performance.

Model 1 was tested again with ground motions scaled 2x to create larger demand forces and displacements and again it was determined that large gravity loads had no significant impact on BRBF performance. Model 2 was tested again with gravity loads applied to the frame consisting of 2x, 4x, 8x, and 16x of the original factored gravity loads and it was determined that gravity loads only had a significant difference on BRBF performance for the unrealistic cases of gravity 8x and 16x.

5.2 Discussion of Gravity and Seismic Loads on a Typical Brace

When the yielding force of a brace is reached the stiffness of the brace drops significantly and it attracts little additional axial forces. The following examples help to illustrate why gravity loads don't seem to have a significant impact on braces. Consider the brace frame in Figure 5-1 and the force-deformation for the brace shown in Figure 5-2.

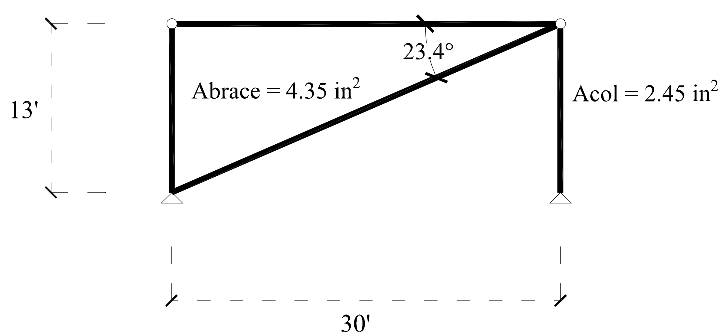

Figure 5-1 Typical brace

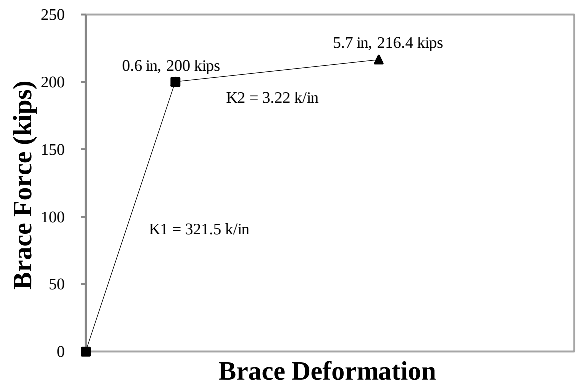

Figure 5-2 Force-deformation for brace

Under an applied gravity load of 86.6 kips the brace has an axial load of 21.8 kips, 10% of the vertical load, and the column has an axial load of 76.6 kips as shown in Figure 5-3. Figure 5-4 is a plot of the brace and column force-deformation from the gravity load.

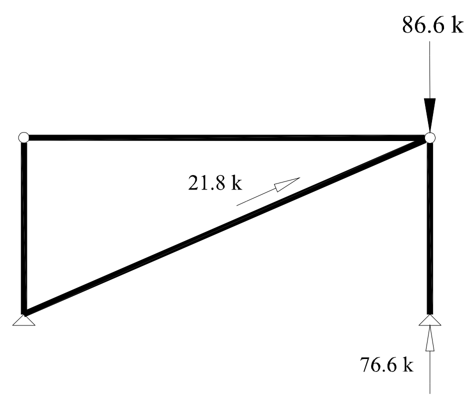

Figure 5-3 Gravity load and reactions on frame

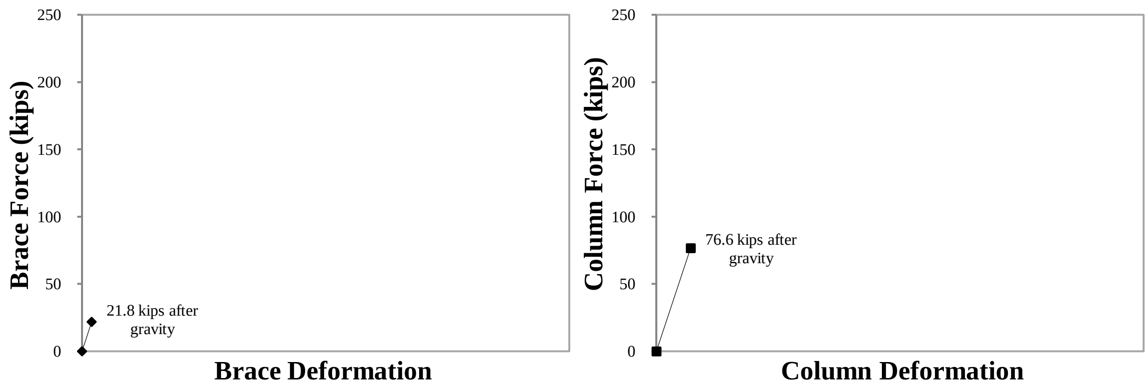

Figure 5-4 Brace and column force-deformation from gravity load

If an additional seismic load of 200 kips is applied as shown in Figure 5-5, it must be resisted by the brace since the columns have no lateral stiffness. For equilibrium the horizontal component of the brace frame must equal 200 kips resulting in a brace axial force of 216.4 kips. In order to determine the reaction at the base of the column, Rcol, the moments are summed at point A (see Figure 5-5). Figure 5-6 is a plot of the brace and column force-deformation from the gravity load.

$\sum M_A = 0 = 200 \text{ kips} * 13 \text{ ft} + 86.6 \text{ kips} * 30 \text{ ft} - Rcol * 30 \text{ ft}$

Rcol = 173.3 kips

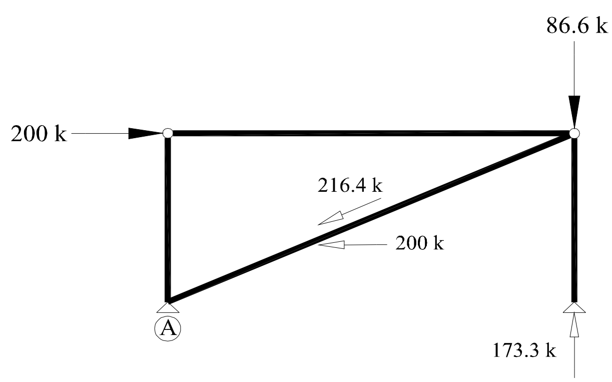

Figure 5-5 Gravity and seismic load and reactions on frame

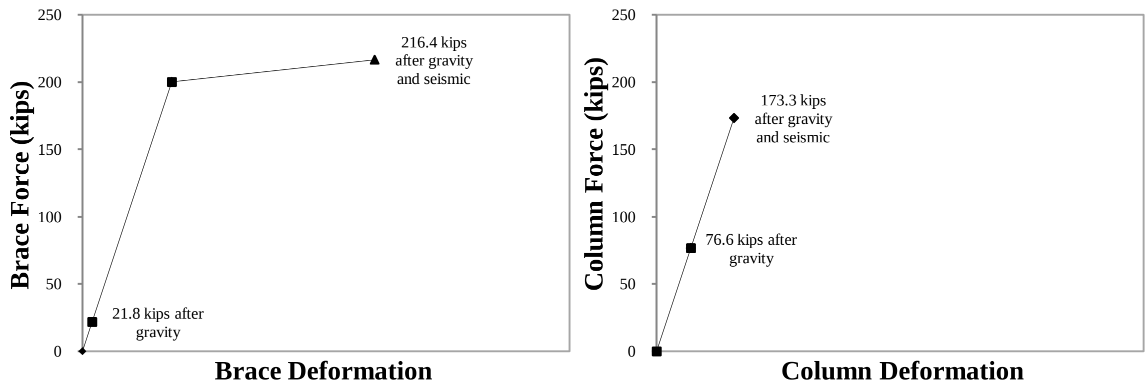

Figure 5-6 Brace and column force-deformation from gravity and seismic load

Now consider the same frame with the seismic load applied first as shown in Figure 5-7 and gravity second. The axial force in the brace is determined to be 216.4 kips and the axial force in the column is 86.7 kips. Figure 5-8 is a plot of the brace and column force-deformation from the seismic load.

$\sum M_A = 0 = 200 \text{ kips} * 13 \text{ ft} - Rcol * 30 \text{ ft}$

$Rcol = 86.7$ kips

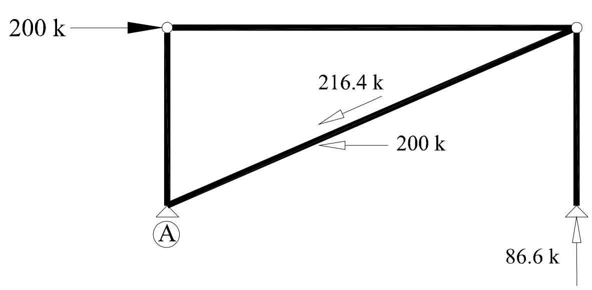

Figure 5-7 Seismic load and reactions on frame

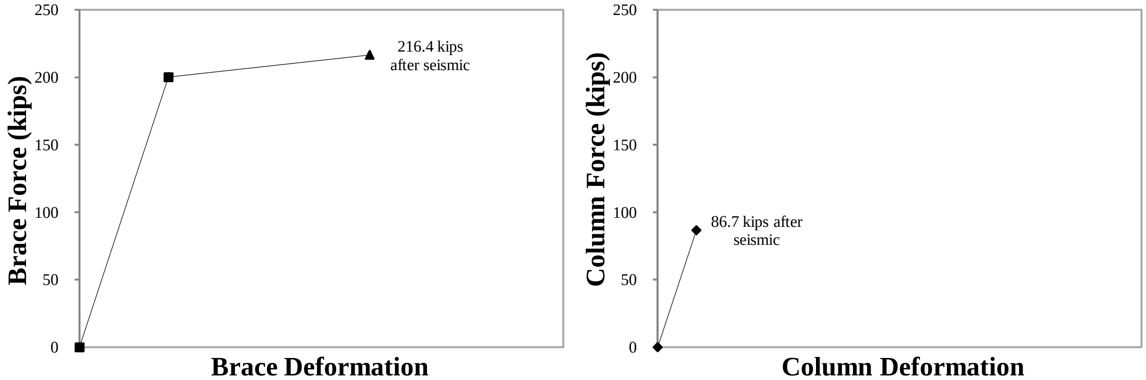

Figure 5-8 Brace and column force-deformation from seismic load

Now consider an applied gravity load of 86.6 kips in addition to the seismic load shown in Figure 5-9. Since the brace has yielded from the seismic load and the stiffness has decreased by an order of magnitude, the brace will not attract any significant gravity load. The vertical forces are summed below. Figure 5-10 is a plot of the brace and column force-deformation from the seismic and gravity load.

$\sum F_v$ = 86.7 kips + 86.6 kips

$\sum F_v$ = 173.3 kips

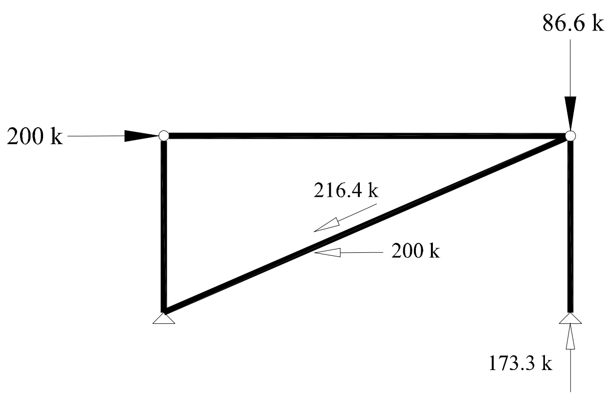

Figure 5-9 Gravity and seismic load and reactions on frame

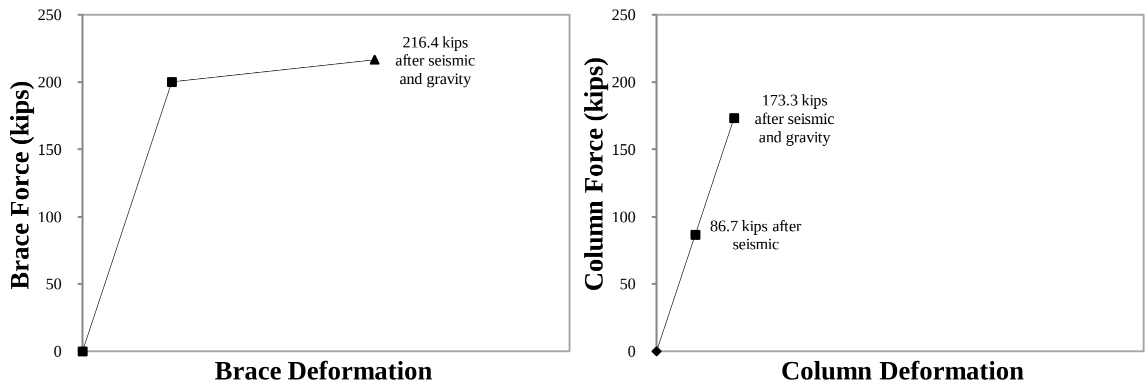

Figure 5-10 Brace and column force-deformation from seismic and gravity load

It is intuitive that yielded braces will no longer carry gravity loads, as discussed in the second case, both cases illustrate how ultimately the loads are the same in the column and brace regardless of order application. From the results it is reasonable to assume that gravity loads of no significant impact on brace performance.

It is concluded that large gravity loads have no significant impact on BRBF performance and that the typical design procedure of neglecting the impact of gravity loads on BRBFs is adequate.

References

Aiken, I.D., S.A. Mahin, and P. Uriz. "Large-scale testing of buckling-restrained braced frames." *Japan Passive Control Symposium.* Tokyo, Japan, 2002.

AISC. *Seismic Design Manual.* AISC, 2006.
—. *Steel Construction Manual.* 2005.

Asgarian, B., and N. Amirhesari. "A comparison of dynamic nonlinear behavior of ordinary and buckling restrained braced frames subjected to strong ground motion." *The Structural Design of Tall and Special Buildings 17, no. 2*, 2008: 367-386.

Black, R. J. N. Makris, and I. D. Aiken. "Component Testing and Modeling of Buckling Restrained "Unbonded" Braces." *Behavior of Steel Structures in Seismic Areas.* Naples, Italy: Stessa, 2003.

Coy, B. B. "Buckling-restrained brace connection design and testing." Master's Thesis, Provo, UT: Brigham Young University, 2007.

Fahnestock, L.A., J. M. Ricles, and R. Sause. "Experimental Evaluation of a Large-Scale Buckling-Restrained Braced Frame." *Journal of Structural Engineering 133, no. 9*, 2007: 1205-1214.

Hussain, S., Benschoten, P.V., Satari, M.A., Lin, S. *Buckling Restrained Braced Frame (BRBF) Structures: Analysis, Design and Approvals Issues.* Nippon Steel News, No. 333, 2005.

Kim, J., and H. Choi. "Behavior and design of structures with buckling-restrained braces." *Engineering Structures*, 2004: 693-706.

Mazzoni, S., F. McKenna, M. H. Scott, and G. L. Fenves. "Open System for Earthquake Engineering Simulation User Command-Language Manual." University of California, Berkeley: Pacific Engineering Research Center, 2006.

Oxborrow, G. T. "Optimized distribution of strength in buckling-restrained brace frames in tall buildings." Master's Thesis, Provo, UT: Brigham Young University, 2009.

Roeder, C. W., D. E. Lehman, and A. Christopulos. "Seismic performance of special concentrically braced frames with buckling restrained braces." *Proceedings of the 8th U.S. National Conference on Earthquake Engineering.* San Francisco, California, 2006.

Sabelli, R., S. Mahin, and C. Chang. "Seismic demands on steel braced frame buildings with buckling-restrained braces." *Engineering Structures 25,* 2003: 655-666.

Takeuchi. T., M. Ida, S. Yamada, and K. Suzuki. "Estimation of cumulative deformation capacity of buckling restrained braces." *Journal of Structural Engineering 134, no. 5,* 2008: 822-831.

Watanabe, A., Y. Hitomi, E. Saeki, A. Wada, and M. Fujimoto. "Properties of brace encased in buckling-restrained concrete and steel tube." *Proceedings of Ninth World Conference on Earthquake Engineering.* Tokyo-Kyoto, Japan, 1988. 719-724.

Appendix A

The source code used for the different models is presented below and can be copied directly into Notepad and saved as a .tcl file and then run in the OpenSees program.

A.1 Model 1 Source Code

```
#Impact of Large Gravity Loads on BRBF Performance
#Mark Matthews - Brigham Young University 2009

# SET UP ------------------------------------------------------------
wipe;                          # clear memory of all past model definitions
model BasicBuilder -ndm 2 -ndf 3;    # Define the model builder
#ndm=#dimension, ndf=#dofs
set dataDir Data;              # set up name of data directory
file mkdir $dataDir;           # create data directory
set GMdir "../GMfiles/";       # ground-motion file directory
source LibUnits.tcl;           # define units
source DisplayModel2D.tcl
source DisplayPlane.tcl
source Wsection.tcl;           # procedure to define fiber W section

# define GEOMETRY ----------------------------------------------------
# define structure-geometry paramters
set LCol1 [expr 21.375*$ft];          # column height
set LCol2 [expr 22*$ft]
set LCol3 [expr 35.75*$ft]
set LCol4 [expr 12.25*$ft]
set LCol5 [expr 31*$ft]
set LCol6 [expr 8*$ft]
set LCol7 [expr 25*$ft]

set L1Beam [expr 40*$ft];             # beam length
```

```
set L2Beam [expr 30*$ft]


# calculate locations of beam/column intersections ------------------
set X1 0.
set X2 [expr $X1 + $L1Beam]
set X3 [expr $X2 + $L2Beam]
set X4 [expr $X3 + $L2Beam]
set X5 [expr $X4 + $L2Beam]
set X6 [expr $X5 + $L2Beam]
set X7 [expr $X6 + $L2Beam]


#x coordinate between beams -----------------------------------------
set X434 [expr $X3 + $L2Beam/2]
set X445 [expr $X4 + $L2Beam/2]
set X456 [expr $X5 + $L2Beam/2]
set X467 [expr $X6 + $L2Beam/2]

set X656 [expr $X5 + $L2Beam/2]
set X667 [expr $X6 + $L2Beam/2]

set X2356 [expr $X2 + 20 *$ft]

set Y1 0
set Y2 [expr $Y1 + $LCol1]
set Y3 [expr $Y2 + $LCol2]
set Y4 [expr $Y3 + $LCol3]
set Y5 [expr $Y4 + $LCol4]
set Y6 [expr $Y5 + $LCol5]
set Y7 [expr $Y6 + $LCol6]
set Y8 [expr $Y7 + $LCol7]
set Y2356 [expr $Y5 + 20 * $ft]


# define nodal coordinates ------------------------------------------
node 11 $X1 $Y1;              # node#, X, Y
node 12 $X2 $Y1
node 13 $X3 $Y1
node 14 $X4 $Y1
node 15 $X5 $Y1
node 16 $X6 $Y1
node 17 $X7 $Y1
node 21 $X1 $Y2
node 22 $X2 $Y2
node 23 $X3 $Y2
```

```
node 24 $X4 $Y2
node 25 $X5 $Y2
node 26 $X6 $Y2
node 27 $X7 $Y2
node 31 $X1 $Y3
node 32 $X2 $Y3
node 33 $X3 $Y3
node 34 $X4 $Y3
node 35 $X5 $Y3
node 36 $X6 $Y3
node 37 $X7 $Y3
node 41 $X1 $Y4
node 42 $X2 $Y4
node 43 $X3 $Y4
node 44 $X4 $Y4
node 45 $X5 $Y4
node 46 $X6 $Y4
node 47 $X7 $Y4
node 51 $X1 $Y5
node 52 $X2 $Y5
node 53 $X3 $Y5
node 54 $X4 $Y5
node 55 $X5 $Y5
node 56 $X6 $Y5
node 57 $X7 $Y5
node 61 $X1 $Y6
node 62 $X2 $Y6
node 63 $X3 $Y6
node 65 $X5 $Y6
node 66 $X6 $Y6
node 67 $X7 $Y6
node 73 $X3 $Y7
node 74 $X4 $Y7
node 75 $X5 $Y7
node 76 $X6 $Y7
node 77 $X7 $Y7
node 83 $X3 $Y8
node 85 $X5 $Y8


#BRBF connection in middle of beams ---------------------------------
node 434 $X434 $Y4
node 445 $X445 $Y4
node 456 $X456 $Y4
node 467 $X467 $Y4
node 656 $X656 $Y6
```

```
node 667 $X667 $Y6


#Single Beam between floor 5 and 6 ----------------------------------
node 562 $X2 $Y2356
node 563 $X2356 $Y2356
node 564 $X3 $Y2356


#Set up parameters that are particular to the model
#for displacement control
set IDctrlNode 83;      # node for displacement control
set IDctrlDOF 1;                # dof for displacement control
set NStory 8;           # number of stories above ground level
set NBay 34;            # number of bays
set LBuilding $Y8;      # total building height


#BOUNDARY CONDITIONS------------------------------------------------
fix 11 1 1 0;           # node DX DY RZ
fix 12 1 1 0
fix 13 1 1 0
fix 14 1 1 0
fix 15 1 1 0
fix 16 1 1 0
fix 17 1 1 0


#Rigid Diaphragm ----------------------------------------------------
equalDOF 21 22 1 2
equalDOF 21 23 1 2
equalDOF 21 24 1 2
equalDOF 21 25 1 2
equalDOF 21 26 1 2
equalDOF 21 27 1 2

equalDOF 31 32 1 2
equalDOF 31 33 1 2
equalDOF 31 34 1 2
equalDOF 31 35 1 2
equalDOF 31 36 1 2
equalDOF 31 37 1 2


equalDOF 41 42 1 2
equalDOF 41 43 1 2
```

```
equalDOF 41 434 1 2
equalDOF 41 44 1 2
equalDOF 41 445 1 2
equalDOF 41 45 1 2
equalDOF 41 456 1 2
equalDOF 41 46 1 2
equalDOF 41 467 1 2
equalDOF 41 47 1 2

equalDOF 51 52 1 2
equalDOF 51 53 1 2
equalDOF 51 54 1 2
equalDOF 51 55 1 2
equalDOF 51 56 1 2
equalDOF 51 57 1 2

equalDOF 562 563 1 2
equalDOF 562 564 1 2

equalDOF 61 62 1 2
equalDOF 61 63 1 2
equalDOF 61 65 1 2
equalDOF 61 656 1 2
equalDOF 61 66 1 2
equalDOF 61 667 1 2
equalDOF 61 67 1 2

equalDOF 73 74 1 2
equalDOF 73 75 1 2
equalDOF 73 76 1 2
equalDOF 73 77 1 2

equalDOF 83 85 1 2


#define MATERIAL properties -----------------------------------------
set Fy [expr 50*$ksi]
set Es [expr 29000*$ksi];                    # Steel Young's Modulus
set nu 0.3
set Gs [expr $Es/2./[expr 1+$nu]];  # Torsional stiffness Modulus
set b_BC 0.01
set R0_BC 20
set cR1_BC 0.925
set cR2_BC 0.15
set FyBrace [expr 1.65*46*$ksi]
set b_Brace 0.025
```

```
set R0_Brace 1.95
set cR1_Brace 0.001
set cR2_Brace 0.001

set BCMat 50
uniaxialMaterial Steel02 $BCMat $Fy $Es $b_BC $R0_BC $cR1_BC $cR2_BC

#define ELEMENTS ---------------------------------------------------
#set up geometric transformations of element
#separate columns and beams, in case of P-Delta analysis for columns
set IDColTransf 100;                    # all columns
set IDBeamTransf 150;                           # all beams
set IDBRBFTransf 200;                           # all BRBFs

geomTransf Corotational $IDColTransf
geomTransf Corotational $IDBeamTransf

# Define Beam-Column Elements
# Gauss integration points for nonlinear curvature distribution
set np 5


#COLUMNS -----------------------------------------------------------
# column sections: W14x311
set d [expr 17.1*$in];          # depth
set bf [expr 16.2*$in];         # flange width
set tf [expr 2.26*$in];         # flange thickness
set tw [expr 1.41*$in];                 # web thickness
set nfdw 16;                    # number of fibers along dw
set nftw 2;                             # number of fibers along tw
set nfbf 16;                    # number of fibers along bf
set nftf 4;                             # number of fibers along tf
Wsection  14311 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf

# column sections: W14x132
set d [expr 14.7*$in]
set bf [expr 14.7*$in]
set tf [expr 1.03*$in]
set tw [expr 0.645*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  14132 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf

# COLUMN section W14x159
```

```
set d [expr 15*$in]
set bf [expr 15.6*$in]
set tf [expr 1.19*$in]
set tw [expr 0.745*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  14159 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf

# COLUMN section W14x176
set d [expr 15.2*$in]
set bf [expr 15.7*$in]
set tf [expr 1.31*$in]
set tw [expr 0.83*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  14176 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf

# COLUMN section W14x398
set d [expr 18.3*$in];
set bf [expr 16.6*$in]
set tf [expr 2.85*$in]
set tw [expr 1.77*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  14398 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf

# COLUMN section W14x68
set d [expr 14*$in]
set bf [expr 10*$in]
set tf [expr 0.72*$in]
set tw [expr 0.415*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  1468 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


#BOX COLUMNS -------------------------------------------------------
#Box COLUMN section E.6-E.A. 2
```

```
set AgColE62 [expr 148*pow($in,2)];          # cross-sectional area
set IzColE62 [expr 10030.*pow($in,4)];       # moment of Inertia
set EIColE62 [expr $Es*$IzColE62];# EI, moment-curvature relationship
set EAColE62 [expr $Es*$AgColE62];           # EA, axial-force-strain relationship

set MyColE62 [expr 4441*$kip*$ft];           # yield moment
set PhiYColE62 [expr 0.172e-3/$in];          # yield curvature
set PhiYColE62 [expr $MyColE62/$EIColE62];      # yield curvature
set EIColCrackE62 [expr $MyColE62/$PhiYColE62];        #     cracked     section inertia

# bilinear behavior for flexure
uniaxialMaterial  Steel02  621  $MyColE62  $EIColCrackE62  $b_BC  $R0_BC $cR1_BC $cR2_BC;
# this is not used as a material, this is an axial-force-strain response
uniaxialMaterial Elastic 622 $EAColE62;
# combine axial and flexural behavior into one section (no P-M interaction here)
section Aggregator 623 622 P 621 Mz;


# Box COLUMN section E.6-E.A. 1
set AgColE61 [expr 188*pow($in,2)]
set IzColE61 [expr 14036.*pow($in,4)]
set EIColE61 [expr $Es*$IzColE61]
set EAColE61 [expr $Es*$AgColE61]


set MyColE61 [expr 5831*$kip*$ft]
set PhiYColE61 [expr 0.172e-3/$in]
set PhiYColE61 [expr $MyColE61/$EIColE61]

set EIColCrackE61 [expr $MyColE61/$PhiYColE61]


uniaxialMaterial  Steel02  611  $MyColE61  $EIColCrackE61  $b_BC  $R0_BC $cR1_BC $cR2_BC
uniaxialMaterial Elastic 612 $EAColE61

section Aggregator 613 612 P 611 Mz



# Box COLUMN section E.7-E.A., E.8-E.A., 3
set AgColE73 [expr 148*pow($in,2)]
```

```
set IzColE73 [expr 10030.*pow($in,4)]

set EIColE73 [expr $Es*$IzColE73]
set EAColE73 [expr $Es*$AgColE73]


set MyColE73 [expr 4441*$kip*$ft]
set PhiYColE73 [expr 0.172e-3/$in]
set PhiYColE73 [expr $MyColE73/$EIColE73]

set EIColCrackE73 [expr $MyColE73/$PhiYColE73]


uniaxialMaterial Steel02 731 $MyColE73 $EIColCrackE73 $b_BC $R0_BC $cR1_BC $cR2_BC
uniaxialMaterial Elastic 732 $EAColE73

section Aggregator 733 732 P 731 Mz



# Box COLUMN section E.7-E.A., E.8-E.A., 2
set AgColE72 [expr 168*pow($in,2)]
set IzColE72 [expr 12133.*pow($in,4)]

set EIColE72 [expr $Es*$IzColE72]
set EAColE72 [expr $Es*$AgColE72]


set MyColE72 [expr 5170*$kip*$ft]
set PhiYColE72 [expr 0.172e-3/$in]
set PhiYColE72 [expr $MyColE72/$EIColE72]

set EIColCrackE72 [expr $MyColE72/$PhiYColE72]


uniaxialMaterial Steel02 721 $MyColE72 $EIColCrackE72 $b_BC $R0_BC $cR1_BC $cR2_BC
uniaxialMaterial Elastic 722 $EAColE72
section Aggregator 723 722 P 721 Mz




# Box COLUMN section E.7-E.A., E.8-E.A., 1
set AgColE71 [expr 224*pow($in,2)]
```

```
set IzColE71 [expr 15839.*pow($in,4)]
set EIColE71 [expr $Es*$IzColE71]
set EAColE71 [expr $Es*$AgColE71]



set MyColE71 [expr 6431*$kip*$ft]
set PhiYColE71 [expr 0.172e-3/$in]
set PhiYColE71 [expr $MyColE71/$EIColE71]
set EIColCrackE71 [expr $MyColE71/$PhiYColE71]

uniaxialMaterial  Steel02  711  $MyColE71  $EIColCrackE71  $b_BC  $R0_BC $cR1_BC $cR2_BC;
uniaxialMaterial Elastic 712 $EAColE71;

section Aggregator 713 712 P 711 Mz;



#BEAMS ---------------------------------------------------------------
# BEAM section W40x211
set d [expr 39.4*$in];          # depth
set bf [expr 11.8*$in];         # flange width
set tf [expr 1.42*$in];         # flange thickness
set tw [expr 0.75*$in];                 # web thickness
set nfdw 16;                    # number of fibers along dw
set nftw 2;                             # number of fibers along tw
set nfbf 16;                    # number of fibers along bf
set nftf 4;                             # number of fibers along tf
Wsection  40211 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W40x235
set d [expr 39.7*$in]
set bf [expr 11.9*$in]
set tf [expr 1.58*$in]
set tw [expr 0.83*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  40235 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W14x193
set d [expr 15.5*$in]
```

```
set bf [expr 15.7*$in]
set tf [expr 1.44*$in]
set tw [expr 0.89*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  14193 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W14x145
set d [expr 14.8*$in]
set bf [expr 15.5*$in]
set tf [expr 1.09*$in]
set tw [expr 0.68*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  14145 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W40x167
set d [expr 38.6*$in]
set bf [expr 11.8*$in]
set tf [expr 1*$in]
set tw [expr 0.65*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  40167 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W40x324
set d [expr 40.2*$in]
set bf [expr 15.9*$in]
set tf [expr 1.81*$in]
set tw [expr 1*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  40324 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf
```

```
# BEAM section W40x431
set d [expr 41.3*$in]
set bf [expr 16.2*$in]
set tf [expr 2.36*$in]
set tw [expr 1.34*$in]
set nfdw 16;
set nftw 2
set nfbf 16
set nftf 4
Wsection  40431 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W24x84
set d [expr 24.1*$in]
set bf [expr 9.02*$in]
set tf [expr 0.77*$in]
set tw [expr 0.47*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  2484 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W24x146
set d [expr 24.7*$in]
set bf [expr 12.9*$in]
set tf [expr 1.09*$in]
set tw [expr 0.65*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  24146 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W40x183
set d [expr 39*$in]
set bf [expr 11.8*$in]
set tf [expr 1.2*$in]
set tw [expr 0.65*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  40183 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf
```

```
# BEAM section W24x162
set d [expr 25*$in]
set bf [expr 13*$in]
set tf [expr 1.22*$in]
set tw [expr 0.705*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  24162 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W30x116
set d [expr 30*$in]
set bf [expr 10.5*$in]
set tf [expr 0.85*$in]
set tw [expr 0.565*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  30116 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W40x149
set d [expr 38.2*$in]
set bf [expr 11.8*$in]
set tf [expr 0.83*$in]
set tw [expr 0.63*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  40149 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# BEAM section W14x233
set d [expr 16*$in]
set bf [expr 15.9*$in]
set tf [expr 1.72*$in]
set tw [expr 1.07*$in]
set nfdw 16
set nftw 2
set nfbf 16
set nftf 4
Wsection  14233 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf
```

```
#Columns -----------------------------------------------------------
#eleTag iNode jNode numIntgrPts SecTag transTag
#level 1
element nonlinearBeamColumn 111 11 21 $np 14311 $IDColTransf
element nonlinearBeamColumn 112 12 22 $np 14311 $IDColTransf
element nonlinearBeamColumn 113 13 23 $np 613 $IDColTransf
element nonlinearBeamColumn 114 14 24 $np 14233 $IDColTransf
element nonlinearBeamColumn 115 15 25 $np 713 $IDColTransf
element nonlinearBeamColumn 116 16 26 $np 14233 $IDColTransf
element nonlinearBeamColumn 117 17 27 $np 713 $IDColTransf

#level 2
element nonlinearBeamColumn 121 21 31 $np 14311 $IDColTransf
element nonlinearBeamColumn 122 22 32 $np 14311 $IDColTransf
element nonlinearBeamColumn 123 23 33 $np 613 $IDColTransf
element nonlinearBeamColumn 124 24 34 $np 14233 $IDColTransf
element nonlinearBeamColumn 125 25 35 $np 713 $IDColTransf
element nonlinearBeamColumn 126 26 36 $np 14233 $IDColTransf
element nonlinearBeamColumn 127 27 37 $np 713 $IDColTransf

#level 3
element nonlinearBeamColumn 131 31 41 $np 14159 $IDColTransf
element nonlinearBeamColumn 132 32 42 $np 14311 $IDColTransf
element nonlinearBeamColumn 133 33 43 $np 623 $IDColTransf
element nonlinearBeamColumn 134 34 44 $np 14233 $IDColTransf
element nonlinearBeamColumn 135 35 45 $np 723 $IDColTransf
element nonlinearBeamColumn 136 36 46 $np 14233 $IDColTransf
element nonlinearBeamColumn 137 37 47 $np 723 $IDColTransf

#level 4
element nonlinearBeamColumn 141 41 51 $np 14159 $IDColTransf
element nonlinearBeamColumn 142 42 52 $np 14311 $IDColTransf
element nonlinearBeamColumn 143 43 53 $np 623 $IDColTransf
element nonlinearBeamColumn 144 44 54 $np 14233 $IDColTransf
element nonlinearBeamColumn 145 45 55 $np 723 $IDColTransf
element nonlinearBeamColumn 146 46 56 $np 14233 $IDColTransf
element nonlinearBeamColumn 147 47 57 $np 723 $IDColTransf


#level 5
element nonlinearBeamColumn 151 51 61 $np 14132 $IDColTransf
element nonlinearBeamColumn 152 52 562 $np 14132 $IDColTransf
element nonlinearBeamColumn 153 53 564 $np 14398 $IDColTransf
element nonlinearBeamColumn 155 55 65 $np 733 $IDColTransf
element nonlinearBeamColumn 156 56 66 $np 14132 $IDColTransf
```

```
element nonlinearBeamColumn 157 57 67 $np 733 $IDColTransf
element nonlinearBeamColumn 158 562 62 $np 14132 $IDColTransf
element nonlinearBeamColumn 159 564 63 $np 14398 $IDColTransf

# level 6
element nonlinearBeamColumn 163 63 73 $np 14398 $IDColTransf
element nonlinearBeamColumn 165 65 75 $np 733 $IDColTransf
element nonlinearBeamColumn 166 66 76 $np 14132 $IDColTransf
element nonlinearBeamColumn 167 67 77 $np 733 $IDColTransf

# level 7
element nonlinearBeamColumn 173 73 83 $np 14176 $IDColTransf
element nonlinearBeamColumn 175 75 85 $np 14132 $IDColTransf


#Beams ------------------------------------------------------------------------
#level 2
element nonlinearBeamColumn 221 21 22 $np 14132 $IDBeamTransf
element nonlinearBeamColumn 222 22 23 $np 14132 $IDBeamTransf
element nonlinearBeamColumn 223 23 24 $np 14132 $IDBeamTransf
element nonlinearBeamColumn 224 24 25 $np 14132 $IDBeamTransf
element nonlinearBeamColumn 225 25 26 $np 14132 $IDBeamTransf
element nonlinearBeamColumn 226 26 27 $np 14132 $IDBeamTransf

#level 3
element nonlinearBeamColumn 331 31 32 $np 40211 $IDBeamTransf
element nonlinearBeamColumn 332 32 33 $np 40211 $IDBeamTransf
element nonlinearBeamColumn 333 33 34 $np 40211 $IDBeamTransf
element nonlinearBeamColumn 334 34 35 $np 40235 $IDBeamTransf
element nonlinearBeamColumn 335 35 36 $np 40211 $IDBeamTransf
element nonlinearBeamColumn 336 36 37 $np 40235 $IDBeamTransf

#level 4
element nonlinearBeamColumn 441 41 42 $np 14132 $IDBeamTransf
element nonlinearBeamColumn 442 42 43 $np 14193 $IDBeamTransf
element nonlinearBeamColumn 443 43 434 $np 14193 $IDBeamTransf
element nonlinearBeamColumn 4431 434 44 $np 14193 $IDBeamTransf
element nonlinearBeamColumn 444 44 445 $np 14193 $IDBeamTransf
element nonlinearBeamColumn 4441 445 45 $np 14193 $IDBeamTransf
element nonlinearBeamColumn 445 45 456 $np 14145 $IDBeamTransf
element nonlinearBeamColumn 4451 456 46 $np 14145 $IDBeamTransf
element nonlinearBeamColumn 446 46 467 $np 14176 $IDBeamTransf
element nonlinearBeamColumn 4461 467 47 $np 14176 $IDBeamTransf

#level 5
element nonlinearBeamColumn 551 51 52 $np 40167 $IDBeamTransf
```

```
element nonlinearBeamColumn 552 52 53 $np 40211 $IDBeamTransf
element nonlinearBeamColumn 553 53 54 $np 40324 $IDBeamTransf
element nonlinearBeamColumn 554 54 55 $np 40431 $IDBeamTransf
element nonlinearBeamColumn 555 55 56 $np 40235 $IDBeamTransf
element nonlinearBeamColumn 556 56 57 $np 40211 $IDBeamTransf

#level 5-6
element nonlinearBeamColumn 5562 562 563 $np 14132 $IDBeamTransf
element nonlinearBeamColumn 5563 563 564 $np 14132 $IDBeamTransf

#level 6
element nonlinearBeamColumn 661 61 62 $np 2484 $IDBeamTransf
element nonlinearBeamColumn 662 62 63 $np 24146 $IDBeamTransf
element nonlinearBeamColumn 663 63 65 $np 40183 $IDBeamTransf
element nonlinearBeamColumn 665 65 656 $np 24146 $IDBeamTransf
element nonlinearBeamColumn 6651 656 66 $np 24146 $IDBeamTransf
element nonlinearBeamColumn 666 66 667 $np 24146 $IDBeamTransf
element nonlinearBeamColumn 6661 667 67 $np 24146 $IDBeamTransf

#level 7
element nonlinearBeamColumn 773 73 74 $np 30116 $IDBeamTransf
element nonlinearBeamColumn 774 74 75 $np 30116 $IDBeamTransf
element nonlinearBeamColumn 775 75 76 $np 24162 $IDBeamTransf
element nonlinearBeamColumn 776 76 77 $np 24162 $IDBeamTransf

#level 8
element nonlinearBeamColumn 883 83 85 $np 40149 $IDBeamTransf


#BRBF Properties --------------------------------------------------
#Effective Modulus of Elasticity for BRBFs
# To Top of 25'
set EeffBRBF11 [expr 48651*$ksi]
set EeffBRBF12 [expr 50108*$ksi]
set EeffBRBF15 [expr 50108*$ksi]
set EeffBRBF16 [expr 50108*$ksi]



# To Top of 47'
set EeffBRBF21 [expr 48200*$ksi]
set EeffBRBF22 [expr 49594*$ksi]
set EeffBRBF25 [expr 49594*$ksi]
set EeffBRBF26 [expr 49594*$ksi]
```

```
# To Top of 83'
set EeffBRBF31 [expr 42670*$ksi]
set EeffBRBF33 [expr 44254*$ksi]
set EeffBRBF34 [expr 44254*$ksi]
set EeffBRBF35 [expr 44254*$ksi]
set EeffBRBF36 [expr 44254*$ksi]


# To Top of 95'
set EeffBRBF41 [expr 63529*$ksi]
set EeffBRBF42 [expr 67001*$ksi]
set EeffBRBF43 [expr 80067*$ksi]
set EeffBRBF44 [expr 80067*$ksi]
set EeffBRBF45 [expr 80067*$ksi]
set EeffBRBF46 [expr 80067*$ksi]
set EeffBRBF47 [expr 80067*$ksi]
set EeffBRBF48 [expr 80067*$ksi]
set EeffBRBF49 [expr 80067*$ksi]
set EeffBRBF410 [expr 80067*$ksi]


# To Top of 126'
set EeffBRBF51 [expr 45967*$ksi]
set EeffBRBF52 [expr 49039*$ksi]
set EeffBRBF55 [expr 48534*$ksi]
set EeffBRBF56 [expr 48534*$ksi]
set EeffBRBF57 [expr 43545*$ksi]
set EeffBRBF58 [expr 44427*$ksi]


# To Top of 134'
set EeffBRBF63 [expr 240262*$ksi]
set EeffBRBF64 [expr 240262*$ksi]
set EeffBRBF65 [expr 128889*$ksi]
set EeffBRBF66 [expr 128889*$ksi]
set EeffBRBF67 [expr 128889*$ksi]
set EeffBRBF68 [expr 128889*$ksi]



# To Top of 159'
set EeffBRBF73 [expr 51364*$ksi]
set EeffBRBF74 [expr 51364*$ksi]
```

```
#Top of 25'
#Area and Effective Modulus of Elasticity for BRBFs
#BRBF 11
set AgBRBF11 [expr 28*pow($in,2)]
set EABRBF11 [expr $EeffBRBF11*$AgBRBF11]; # EA, axial-force-strain relationship


# BRBF 12
set AgBRBF12 [expr 16*pow($in,2)]
set EABRBF12 [expr $EeffBRBF12*$AgBRBF12]


#BRBF 15
set AgBRBF15 [expr 48*pow($in,2)]
set EABRBF15 [expr $EeffBRBF15*$AgBRBF15]


#BRBF 16
set AgBRBF16 [expr 48*pow($in,2)]
set EABRBF16 [expr $EeffBRBF16*$AgBRBF16]


#Top of 47'
#BRBF 21
set AgBRBF21 [expr 16*pow($in,2)]
set EABRBF21 [expr $EeffBRBF21*$AgBRBF21]


#BRBF 22
set AgBRBF22 [expr 28*pow($in,2)]
set EABRBF22 [expr $EeffBRBF22*$AgBRBF22]


#BRBF 25
set AgBRBF25 [expr 48*pow($in,2)]
set EABRBF25 [expr $EeffBRBF25*$AgBRBF25]




#BRBF 26
set AgBRBF26 [expr 48*pow($in,2)]
set EABRBF26 [expr $EeffBRBF26*$AgBRBF26]
```

```
#Top of 83'
#BRBF 31
set AgBRBF31 [expr 26*pow($in,2)]
set EABRBF31 [expr $EeffBRBF31*$AgBRBF31]


#BRBF 33
set AgBRBF33 [expr 32*pow($in,2)]
set EABRBF33 [expr $EeffBRBF33*$AgBRBF33]


#BRBF 34
set AgBRBF34 [expr 32*pow($in,2)]
set EABRBF34 [expr $EeffBRBF34*$AgBRBF34]


#BRBF 35
set AgBRBF35 [expr 24*pow($in,2)]
set EABRBF35 [expr $EeffBRBF35*$AgBRBF35]


#BRBF 36
set AgBRBF36 [expr 18*pow($in,2)]
set EABRBF36 [expr $EeffBRBF36*$AgBRBF36]


#Top of 83'
#BRBF 41
set AgBRBF41 [expr 4*pow($in,2)]
set EABRBF41 [expr $EeffBRBF41*$AgBRBF41]


#BRBF 42
set AgBRBF42 [expr 24*pow($in,2)]
set EABRBF42 [expr $EeffBRBF42*$AgBRBF42]


#BRBF 43
set AgBRBF43 [expr 16*pow($in,2)]
set EABRBF43 [expr $EeffBRBF43*$AgBRBF43]


#BRBF 44
set AgBRBF44 [expr 32*pow($in,2)]
set EABRBF44 [expr $EeffBRBF44*$AgBRBF44]
```

```
#BRBF 45
set AgBRBF45 [expr 32*pow($in,2)]
set EABRBF45 [expr $EeffBRBF45*$AgBRBF45]


#BRBF 46
set AgBRBF46 [expr 16*pow($in,2)]
set EABRBF46 [expr $EeffBRBF46*$AgBRBF46]


#BRBF 47
set AgBRBF47 [expr 16*pow($in,2)]
set EABRBF47 [expr $EeffBRBF47*$AgBRBF47]


#BRBF 48
set AgBRBF48 [expr 20*pow($in,2)]
set EABRBF48 [expr $EeffBRBF48*$AgBRBF48]


#BRBF 49
set AgBRBF49 [expr 14*pow($in,2)]
set EABRBF49 [expr $EeffBRBF49*$AgBRBF49]


#BRBF 410
set AgBRBF410 [expr 12*pow($in,2)]
set EABRBF410 [expr $EeffBRBF410*$AgBRBF410]


#Top of 95'
#BRBF 51
set AgBRBF51 [expr 12*pow($in,2)]
set EABRBF51 [expr $EeffBRBF51*$AgBRBF51]


#BRBF 52
set AgBRBF52 [expr 8*pow($in,2)]
set EABRBF52 [expr $EeffBRBF52*$AgBRBF52]


#BRBF 55
set AgBRBF55 [expr 8*pow($in,2)]
set EABRBF55 [expr $EeffBRBF55*$AgBRBF55]
```

```
#BRBF 56
set AgBRBF56 [expr 12*pow($in,2)]
set EABRBF56 [expr $EeffBRBF56*$AgBRBF56]


#BRBF 57
set AgBRBF57 [expr 10*pow($in,2)]
set EABRBF57 [expr $EeffBRBF57*$AgBRBF57]


#BRBF 58
set AgBRBF58 [expr 4*pow($in,2)]
set EABRBF58 [expr $EeffBRBF58*$AgBRBF58]


#Top of 126'
#BRBF 63
set AgBRBF63 [expr 6*pow($in,2)]
set EABRBF63 [expr $EeffBRBF63*$AgBRBF63]


#BRBF 64
set AgBRBF64 [expr 6*pow($in,2)]
set EABRBF64 [expr $EeffBRBF64*$AgBRBF64]


#BRBF 65
set AgBRBF65 [expr 4*pow($in,2)]
set EABRBF65 [expr $EeffBRBF65*$AgBRBF65]


#BRBF 66
set AgBRBF66 [expr 12*pow($in,2)]
set EABRBF66 [expr $EeffBRBF66*$AgBRBF66]


#BRBF 67
set AgBRBF67 [expr 20*pow($in,2)]
set EABRBF67 [expr $EeffBRBF67*$AgBRBF67]


#BRBF 68
set AgBRBF68 [expr 4*pow($in,2)]
set EABRBF68 [expr $EeffBRBF68*$AgBRBF68]
```

```
#Top of 159'
#BRBF 73
set AgBRBF73 [expr 2.5*pow($in,2)]
set EABRBF73 [expr $EeffBRBF73*$AgBRBF73]


#BRBF 74
set AgBRBF74 [expr 2.5*pow($in,2)]
set EABRBF74 [expr $EeffBRBF74*$AgBRBF74]


#BRBFs ------------------------------------------------------------
uniaxialMaterial Steel02 11111 $FyBrace $EeffBRBF11 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 11211 $FyBrace $EeffBRBF12 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 11511 $FyBrace $EeffBRBF15 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 11611 $FyBrace $EeffBRBF16 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace

uniaxialMaterial Steel02 22121 $FyBrace $EeffBRBF21 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 22221 $FyBrace $EeffBRBF22 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 22521 $FyBrace $EeffBRBF25 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 22621 $FyBrace $EeffBRBF26 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace

uniaxialMaterial Steel02 33131 $FyBrace $EeffBRBF31 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 33331 $FyBrace $EeffBRBF33 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 33431 $FyBrace $EeffBRBF34 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 33531 $FyBrace $EeffBRBF35 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 33631 $FyBrace $EeffBRBF36 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace

uniaxialMaterial Steel02 44141 $FyBrace $EeffBRBF41 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 44241 $FyBrace $EeffBRBF42 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
```

uniaxialMaterial Steel02 44341 $FyBrace $EeffBRBF43 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 44441 $FyBrace $EeffBRBF44 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 44541 $FyBrace $EeffBRBF45 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 44641 $FyBrace $EeffBRBF46 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 44741 $FyBrace $EeffBRBF47 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 44841 $FyBrace $EeffBRBF48 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 44941 $FyBrace $EeffBRBF49 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 441041 $FyBrace $EeffBRBF410 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace

uniaxialMaterial Steel02 55151 $FyBrace $EeffBRBF51 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 55251 $FyBrace $EeffBRBF52 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 55551 $FyBrace $EeffBRBF55 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 55651 $FyBrace $EeffBRBF56 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 55751 $FyBrace $EeffBRBF57 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 55851 $FyBrace $EeffBRBF58 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace

uniaxialMaterial Steel02 66361 $FyBrace $EeffBRBF63 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 66461 $FyBrace $EeffBRBF64 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 66561 $FyBrace $EeffBRBF65 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 66661 $FyBrace $EeffBRBF66 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 66761 $FyBrace $EeffBRBF67 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 66861 $FyBrace $EeffBRBF68 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace

uniaxialMaterial Steel02 77371 $FyBrace $EeffBRBF73 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace

```
uniaxialMaterial Steel02 77471 $FyBrace $EeffBRBF74 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace


#BRBFs --------------------------------------------------------------
#eleTag iNode jNode A matTag
#BRBF level 1-2
element corotTruss 11 11 22 $AgBRBF11 11111
element corotTruss 12 13 22 $AgBRBF12 11211
element corotTruss 15 15 26 $AgBRBF15 11511
element corotTruss 16 17 26 $AgBRBF16 11611

#BRBF level 2-3
element corotTruss 21 22 31 $AgBRBF21 22121
element corotTruss 22 22 33 $AgBRBF22 22221
element corotTruss 25 26 35 $AgBRBF25 22521
element corotTruss 26 26 37 $AgBRBF26 22621

#BRBF level 3-4
element corotTruss 31 42 31 $AgBRBF31 33131
element corotTruss 33 33 434 $AgBRBF33 33331
element corotTruss 34 35 445 $AgBRBF34 33431
element corotTruss 35 35 456 $AgBRBF35 33531
element corotTruss 36 37 467 $AgBRBF36 33631

#BRBF level 4-5
element corotTruss 41 42 51 $AgBRBF41 44141
element corotTruss 42 42 53 $AgBRBF42 44241
element corotTruss 43 434 53 $AgBRBF43 44341
element corotTruss 44 434 54 $AgBRBF44 44441
element corotTruss 45 445 54 $AgBRBF45 44541
element corotTruss 46 445 55 $AgBRBF46 44641
element corotTruss 47 456 55 $AgBRBF47 44741
element corotTruss 48 456 56 $AgBRBF48 44841
element corotTruss 49 467 56 $AgBRBF49 44941
element corotTruss 410 467 57 $AgBRBF410 441041

#BRBF level 5-6
element corotTruss 51 51 62 $AgBRBF51 55151
element corotTruss 52 53 563 $AgBRBF52 55251
element corotTruss 55 55 656 $AgBRBF55 55551
element corotTruss 56 57 667 $AgBRBF56 55651
element corotTruss 57 563 62 $AgBRBF57 55751
element corotTruss 58 563 63 $AgBRBF58 55851
```

```
#BRBF level 6-7
element corotTruss 63 63 74 $AgBRBF63 66361
element corotTruss 64 65 74 $AgBRBF64 66461
element corotTruss 65 656 75 $AgBRBF65 66561
element corotTruss 66 656 76 $AgBRBF66 66661
element corotTruss 67 667 76 $AgBRBF67 66761
element corotTruss 68 667 77 $AgBRBF68 66861

#BRBF level 7-8
element corotTruss 73 74 83 $AgBRBF73 77371
element corotTruss 74 74 85 $AgBRBF74 77471


#Define RECORDERS ---------------------------------------------------
recorder Drift -file $dataDir/Drift.out -time -iNode 11 21 31 41 51 63 73 -jNode 21 31 41 51 61 73 83 -dof 1  -perpDirn 2 ;    # lateral drift
recorder Element -file $dataDir/BraceAxialBRBF.out -time -ele 11 12 15 16 21 22 25 26 31 33 34 35 36 41 42 43 44 45 46 47 48 49 410 51 52 55 56 57 58 63 64 65 66 67 68 73 74 axialForce
recorder Element -file $dataDir/DeformationBRBF.out -time -ele 11 12 15 16 21 22 25 26 31 33 34 35 36 41 42 43 44 45 46 47 48 49 410 51 52 55 56 57 58 63 64 65 66 67 67 73 74 deformations
recorder plot -file $dataDir/display.out window $X7 $Y8 640 640 -columns 111 111


#Masses ------------------------------------------------------------
mass 22  [expr (727*$kip)/$g] 0. 0.
mass 26  [expr (1635*$kip)/$g] 0. 0.

mass 31  [expr (1902*$kip)/$g] 0. 0.
mass 33  [expr (3460*$kip)/$g] 0. 0.
mass 35  [expr (5931*$kip)/$g] 0. 0.
mass 37  [expr (5931*$kip)/$g] 0. 0.

mass 42  [expr (865*$kip)/$g] 0. 0.
mass 434  [expr (397*$kip)/$g] 0. 0.
mass 445  [expr (397*$kip)/$g] 0. 0.
mass 456  [expr (298*$kip)/$g] 0. 0.
mass 467  [expr (223*$kip)/$g] 0. 0.


mass 51  [expr (446*$kip)/$g] 0. 0.
mass 53  [expr (5737*$kip)/$g] 0. 0.
mass 54  [expr (10018*$kip)/$g] 0. 0.
mass 55  [expr (5009*$kip)/$g] 0. 0.
```

```
mass 56  [expr (5322*$kip)/$g] 0. 0.
mass 57  [expr (1878*$kip)/$g] 0. 0.

mass 62  [expr (3458*$kip)/$g] 0. 0.
mass 63  [expr (176*$kip)/$g] 0. 0.
mass 656  [expr (669*$kip)/$g] 0. 0.
mass 667  [expr (1004*$kip)/$g] 0. 0.

mass 74  [expr (1613*$kip)/$g] 0. 0.
mass 75  [expr (819*$kip)/$g] 0. 0.
mass 76  [expr (6550*$kip)/$g] 0. 0.
mass 77  [expr (819*$kip)/$g] 0. 0.

mass 83  [expr (80*$kip)/$g] 0. 0.
mass 85  [expr (80*$kip)/$g] 0. 0.


#calculate total Floor Mass -----------------------------------------
set WeightFloor2 [expr 727*$kip + 1635*$kip]
set WeightFloor3 [expr 1902*$kip + 3460*$kip + 5931*$kip + 5931*$kip]
set WeightFloor4 [expr 865*$kip + 397*$kip + 397*$kip + 298*$kip + 223*$kip]
set WeightFloor5 [expr 446*$kip + 5737*$kip + 10018*$kip + 5009*$kip + 5322*$kip + 1878*$kip]
set WeightFloor6 [expr 3458*$kip + 176*$kip + 669*$kip + 1004*$kip]
set WeightFloor7 [expr 1613*$kip + 819*$kip + 6550*$kip + 819*$kip]
set WeightFloor8 [expr 80*$kip + 80*$kip]

set MassFloor2 [expr $WeightFloor2/$g]
set MassFloor3 [expr $WeightFloor3/$g]
set MassFloor4 [expr $WeightFloor4/$g]
set MassFloor5 [expr $WeightFloor5/$g]
set MassFloor6 [expr $WeightFloor6/$g]
set MassFloor7 [expr $WeightFloor7/$g]
set MassFloor8 [expr $WeightFloor8/$g]

#total frame mass
set MassTotal [expr $MassFloor2 + $MassFloor3 + $MassFloor4 + $MassFloor5 + $MassFloor6 + $MassFloor7 + $MassFloor8]



#total frame weight
set WeightTotal [expr $MassTotal * $g]
```

```
#define GRAVITY Loads -----------------------------------------------
#NOTE - For Model with No Gravity Loads Comment Out this Section
set WzBeam21 [expr 5*$kip]
set WzBeam22 [expr 4*$kip]
set WzBeam23 [expr 4*$kip]
set WzBeam24 [expr 4*$kip]
set WzBeam25 [expr 4*$kip]
set WzBeam26 [expr 4*$kip]
set WzBeam27 [expr 4*$kip]

set WzBeam31 [expr 76*$kip]
set WzBeam32 [expr 53*$kip]
set WzBeam33 [expr 610*$kip]
set WzBeam34 [expr 46*$kip]
set WzBeam35 [expr 686*$kip]
set WzBeam36 [expr 46*$kip]
set WzBeam37 [expr 686*$kip]

set WzBeam41 [expr 5*$kip]
set WzBeam42 [expr 6*$kip]
set WzBeam43 [expr 6*$kip]
set WzBeam44 [expr 6*$kip]
set WzBeam45 [expr 6*$kip]
set WzBeam46 [expr 4*$kip]
set WzBeam47 [expr 5*$kip]

set WzBeam51 [expr 76*$kip]
set WzBeam52 [expr 53*$kip]
set WzBeam53 [expr 610*$kip]
set WzBeam54 [expr 46*$kip]
set WzBeam55 [expr 686*$kip]
set WzBeam56 [expr 46*$kip]
set WzBeam57 [expr 686*$kip]

set WzBeam61 [expr 73*$kip]
set WzBeam62 [expr 128*$kip]
set WzBeam63 [expr 280*$kip]
set WzBeam65 [expr 187*$kip]
set WzBeam66 [expr 125*$kip]
set WzBeam67 [expr 187*$kip]


set WzBeam73 [expr 68*$kip]
set WzBeam75 [expr 103*$kip]
set WzBeam76 [expr 68*$kip]
set WzBeam77 [expr 410*$kip]
```

```
set WzBeam83 [expr 25*$kip]
set WzBeam85 [expr 25*$kip]

pattern Plain 1 Linear {
  load 21 0 -$WzBeam21 0
  load 22 0 -$WzBeam22 0
  load 23 0 -$WzBeam23 0
  load 24 0 -$WzBeam24 0
  load 25 0 -$WzBeam25 0
  load 26 0 -$WzBeam26 0
  load 27 0 -$WzBeam27 0

  load 31 0 -$WzBeam31 0
  load 32 0 -$WzBeam32 0
  load 33 0 -$WzBeam33 0
  load 34 0 -$WzBeam34 0
  load 35 0 -$WzBeam35 0
  load 36 0 -$WzBeam36 0
  load 37 0 -$WzBeam37 0

  load 41 0 -$WzBeam41 0
  load 42 0 -$WzBeam42 0
  load 43 0 -$WzBeam43 0
  load 44 0 -$WzBeam44 0
  load 45 0 -$WzBeam45 0
  load 46 0 -$WzBeam46 0
  load 47 0 -$WzBeam47 0

  load 51 0 -$WzBeam51 0
  load 52 0 -$WzBeam52 0
  load 53 0 -$WzBeam53 0
  load 54 0 -$WzBeam54 0
  load 55 0 -$WzBeam55 0
  load 56 0 -$WzBeam56 0
  load 57 0 -$WzBeam57 0

  load 61 0 -$WzBeam61 0
  load 62 0 -$WzBeam62 0
  load 65 0 -$WzBeam65 0
  load 66 0 -$WzBeam66 0
  load 67 0 -$WzBeam67 0

  load 73 0 -$WzBeam73 0
  load 75 0 -$WzBeam75 0
  load 76 0 -$WzBeam76 0
```

```
  load 77 0 -$WzBeam77 0

  load 83 0 -$WzBeam83 0
  load 85 0 -$WzBeam85 0
}


# Gravity-analysis parameters -- load-controlled static analysis ------
set Tol 1.0e-8;			# convergence tolerance for test
variable constraintsTypeGravity Plain;		# default;
if {  [info exists RigidDiaphragm] == 1} {
	if {$RigidDiaphragm=="ON"} {
		variable constraintsTypeGravity Lagrange;	#	large model: try Transformation
	};	# if rigid diaphragm is on
};	# if rigid diaphragm exists
constraints $constraintsTypeGravity;	# how it handles boundary conditions
numberer RCM;	# renumber dof's to minimize band-width (optimization), if you want to
system BandGeneral;# how to store and solve the system of equations in the analysis (large model: try UmfPack)
test NormDispIncr $Tol 6; # determine if convergence has been achieved at the end of an iteration step
algorithm Newton;# use Newton's solution algorithm: updates tangent stiffness at every iteration
set NstepGravity 10;  # apply gravity in 10 steps
set DGravity [expr 1./$NstepGravity];	# first load increment;
integrator LoadControl $DGravity;	# determine the next time step for an analysis
analysis Static;			# define type of analysis static or transient
analyze $NstepGravity;		# apply gravity

# ------------------------------ maintain constant gravity loads and reset time to zero
loadConst -time 0.0

# ------------PeriodFreq&Damping.tcl----------------------------------

# determine Natural Period, Frequency & damping parameters for SDOF

set xDamp 0.02; # damping ratio (0.02-0.05-typical)
set lambda [eigen 1]
set omega [expr pow($lambda,0.5)]
set Tperiod [expr 2*$PI/$omega]; # period (sec.)
puts $Tperiod
set alphaM 0; # stiffness-prop. RAYLEIGH damping parameter; D = alphaM*M
```

```
set betaK 0; # stiffness proportional damping; +beatK*KCurrent
set betaKcomm [expr 2*$xDamp/$omega]; # mass-prop. RAYLEIGH damping parameter; +betaKcomm*KlastCommitt
set betaKinit 0; # initial-stiffness proportional damping +beatKinit*Kini


puts "Model Built"
DisplayModel2D NodeNumbers
```

A.2 Relative Stiffness and Weight Calculations for BRBFs

The same modulus of elasticity, E, is used for all BRBs since each stiffness is relative to total stiffness. Weights were divided by gravity in the model to obtain the mass placed on the model frame. The following equations were used to determine BRB stiffness and seismic weight placed on each node.

$$K = \frac{EA}{Lbr} * \left(\frac{L}{Lbr} \right)^2 \qquad \textbf{(A-1)}$$

$$W = \frac{K}{Kt} * Wt \qquad \textbf{(A-2)}$$

where *K* is the stiffness of the BRB, *E* is the modulus of elasticity of the material being 29,000 ksi, *A* is the area of the BRB, *L* is the length of the bay, and *Lbr* is the length of the BRB. *W* is the seismic weight relative to brace stiffness, *Kt* is the sum of BRB stiffness for the total story level, and *Wt* is the sum of seismic weight for the total story level.

Tables A-1 through A-4 are for the 2^{nd} level with a story height of 21.375 ft, *Kt* being 18611 k/in, and *Wt* being 7285 kips.

Table A-1 Bf-1 second level

bf-1	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	28	40	45.35	1161	454	22	727
E.5 to E.6	16	30	36.84	696	273		
E.7 to E.7.5	48	30	36.84	2089	818	26	1635
E.7.5 to E8	48	30	36.84	2089	818		
E.9 to E.9.5	16	30	36.84	696	273		
E.9.5 to E.10	36	30	36.84	1567	613		
			Total	**8297**	**3248**	%	**45%**

Table A-2 Bf-2 second level

bf-2	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	24	40	45.35	995	389		
E.5 to E.6	24	30	36.84	1044	409		
E.7 to E.7.5	24	30	36.84	1044	409		
E.7.5 to E.8	24	30	36.84	1044	409		
E.9 to E.9.5	24	30	36.84	1044	409		
E.9.5 to E.10	24	30	36.84	1044	409		
			Total	**6217**	**2433**	%	**33%**

Table A-3 Bf-5 second level

bf-5	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.4	24	30	36.84	1044	409		
E.4 to E.5	24	30	36.84	1044	409		
			Total	**2089**	**818**	%	**11%**

Table A-4 Bf-6 second level

bf-6	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.3.5	24	23	31.40	991	388		
E.3.5 to E.5	24	37	42.73	1018	398		
			Total	**2009**	**786**	%	**11%**

Tables A-5 through A-8 are for the 3rd level with a story height of 22 ft, *Kt* being 18104 k/in, and *Wt* being 52955 kips.

Table A-5 Bf-1 third level

bf-1	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	16	40	45.65	650	1902	31	1902
E.5 to E.6	28	30	37.20	1183	3460	33	3460
E.7 to E.7.5	48	30	37.20	2028	5931	35	5931
E.7.5 to E8	48	30	37.20	2028	5931	37	5931
E.9 to E.9.5	36	30	37.20	1521	4448		
E.9.5 to E.10	16	30	37.20	676	1977		
			Total	**8085**	**23649**	%	**45%**

Table A-6 Bf-2 third level

bf-2	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	24	40	45.65	975	2853		
E.5 to E.6	24	30	37.20	1014	2965		
E.7 to E.7.5	24	30	37.20	1014	2965		
E.7.5 to E.8	24	30	37.20	1014	2965		
E.9 to E.9.5	24	30	37.20	1014	2965		
E.9.5 to E.10	24	30	37.20	1014	2965		
			Total	**6045**	**17680**	%	**33%**

Table A-7 Bf-5 third level

bf-5	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.4	24	30	37.20	1014	2965		
E.4 to E.5	24	30	37.20	1014	2965		
			Total	**2028**	**5931**	%	**11%**

Table A-8 Bf-6 third level

bf-6	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.3.5	24	23	31.83	952	2784		
E.3.5 to E.5	24	37	43.05	995	2912		
			Total	**1947**	**5695**	%	**11%**

Tables A-9 through A-11 are for a intermediate level between the 3rd and 4th level located in a different portion of the structure with a story height of 24 ft, *Kt* being 5920 k/in, and *Wt* being 2821 kips.

Table A-9 Bf-2 intermediate level

bf-2	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	14	40	46.65	533	254		
E.5 to E.6	14	30	38.42	537	256		
E.7 to E.7.5	14	30	38.42	537	256		
E.7.5 to E.8	14	30	38.42	537	256		
E.9 to E.9.5	14	30	38.42	537	256		
E.9.5 to E.10	14	30	38.42	537	256		
			Total	**3218**	**1534**	%	**54%**

Table A-10 Bf-5 intermediate level

bf-5	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.4	18	30	38.42	690	329		
E.4 to E.5	18	30	38.42	690	329		
			Total	**1381**	**658**	%	**23%**

Table A-11 Bf-6 intermediate level

bf-6	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.3.5	18	23	33.24	626	299		
E.3.5 to E.5	18	37	44.10	694	331		
			Total	**1321**	**629**	%	**22%**

Table A-12 is for the 4th level with a story height of 35.75 ft, *Kt* being 1976 k/in, and *Wt* being 2626 kips.

Table A-12 Bf-1 fourth level

bf-1	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	26	40	53.65	651	865	42	865
E.6 to E.6.25	32	15	38.77	299	397	434	397
E.6.75 to E.7	32	15	38.77	299	397	445	397
E.7 to E.7.25	24	15	38.77	224	298	456	298
E.7.75 to E.8	18	15	38.77	168	223	467	223
E.9 to E.9.25	18	15	38.77	168	223		
E.9.75 to E.10	18	15	38.77	168	223		
			Total	**1976**	**2626**	%	**100%**

Tables A-13 through A-16 are for the fifth level and intermediate levels between the 4th and 5th level located in a different portion of the structure with story heights of 12.38 and 24 ft, *Kt* being 23958 k/in, and *Wt* being 50711 kips.

Table A-13 Bf-1 fifth level and intermediate levels

bf-1	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	4	40	41.87	211	446	51	446
E.5 to E.6	24	30	32.45	1527	3233		
E.6 to E.6.25	16	15	19.45	1183	2504	53	5737
E.6.25 to E.6.5	32	15	19.45	2366	5009		
E.6.5 to E.6.75	32	15	19.45	2366	5009	54	10018
E.6.75 to E.7	16	15	19.45	1183	2504		
E.7 to E.7.25	16	15	19.45	1183	2504	55	5009
E.7.25 to E.7.5	20	15	19.45	1479	3131		
E.7.5 to E.7.75	14	15	19.45	1035	2191	56	5322
E.7.75 to E.8	12	15	19.45	887	1878	57	1878
E.9 to E.9.25	12	15	19.45	887	1878		
E.9.25 to E.9.5	14	15	19.45	1035	2191		
E.9.5 to E.9.75	14	15	19.45	1035	2191		
E.9.75 to E.10	12	15	19.45	887	1878		
			Total	**17267**	**36549**	%	**72%**

Table A-14 Bf-2 fifth level and intermediate levels

bf-2	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	14	40	46.65	533	1129		
E.5 to E.6	14	30	38.42	537	1137		
E.7 to E.7.5	14	30	38.42	537	1137		
E.7.5 to E.8	14	30	38.42	537	1137		
E.9 to E.9.5	14	30	38.42	537	1137		
E.9.5 to E.10	14	30	38.42	537	1137		
			Total	**3218**	**6812**	%	**13%**

Table A-15 Bf-5 fifth level and intermediate levels

bf-5	A (in²)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.4	24	30	37.20	1014	2146		
E.4 to E.5	18	30	37.20	760	1610		
			Total	**1774**	**3756**	%	**7%**

Table A-16 Bf-6 fifth level and intermediate levels

bf-6	A (in²)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.3.5	24	23	31.83	952	2014		
E.3.5 to E.5	18	37	43.05	747	1580		
			Total	**1698**	**3595**	%	**7%**

Table A-17 through A-20 are for the 6th level with a story height of 31 ft, *Kt* being 2599 k/in, and *Wt* being 16324 kips.

Table A-17 Bf-1 sixth level

bf-1	(in²)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	12	40	50.61	358	2249		
E.5 to E.5.5	10	20	36.89	193	1209	62	3458
E.5.5 to E.6	4	10	32.57	28	176	63	176
E.7 to E.7.25	8	15	34.44	107	669	656	669
E.7.75 to E.8	12	15	34.44	160	1004	667	1004
E.9 to E.9.25	8	15	34.44	107	669		
E.9.75 to E.10	6	15	34.44	80	502		
			Total	**1031**	**6478**	%	**40%**

Table A-18 Bf-2 sixth level

bf-2	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.3 to E.5	6	40	50.61	179	1124		
E.5 to E.6	4	30	43.14	108	681		
E.7 to E.7.5	4	30	43.14	108	681		
E.7.5 to E.8	4	30	43.14	108	681		
E.9 to E.9.5	4	30	43.14	108	681		
E.9.5 to E.10	4	30	43.14	108	681		
			Total	**721**	**4528**	%	

Table A-19 Bf-5 sixth level

bf-5	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.4	8	30	43.14	217	1361		
E.4 to E.5	8	30	43.14	217	1361		
			Total	**433**	**2723**	%	**17%**

Table A-20 Bf-6 sixth level

bf-6	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.2 to E.3.5	8	23	38.60	178	1117		
E.3.5 to E.5	8	37	48.27	235	1478		
			Total	**413**	**2595**	%	**16%**

Table A-21 through A-25 are for the 7th level with differing story heights of 8 and 39 ft, *Kt* being 13065 k/in, and *Wt* being 24164 kips.

Table A-21 Bf-1 seventh level

bf-1	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.6 to E.6.5	6	30	31.05	436	806		
E.6.5 to E.7	6	30	31.05	436	806	74	1613
E.7 to E.7.25	4	15	17.00	443	819	75	819
E.7.25 to E.7.5	12	15	17.00	1328	2456		
E.7.5 to E.7.75	20	15	17.00	2214	4094	76	6550
E.7.75 to E.8	4	15	17.00	443	819	77	819
E.9 to E.9.25	4	15	17.00	443	819		
E.9.25 to E.9.5	12	15	17.00	1328	2456		
E.9.5 to E.9.75	6	15	17.00	664	1228		
E.9.75 to E.10	6	15	17.00	664	1228		
			Total	**8398**	**15532**	%	**64%**

Table A-22 Bf-7 seventh level

bf-7	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.6 to E.6.5	22	30	49.20	402	743		
E.6.5 to E.7	22	30	49.20	402	743		
E.9 to E.9.5	22	30	49.20	402	743		
E.9.5 to E.10	22	30	49.20	402	743		
			Total	**1607**	**2972**	%	**12%**

Table A-23 Bf-8 seventh level

bf-8	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.6 to E.6.5	22	30	49.20	402	743		
E.6.5 to E.7	22	30	49.20	402	743		
E.9 to E.9.5	22	30	49.20	402	743		
E.9.5 to E.10	22	30	49.20	402	743		
			Total	**1607**	**2972**	%	**12%**

Table A-24 Bf-18 seventh level

bf-18	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.6 to E.6.5	6	30	31.05	436	806		
E.6.5 to E.7	4	30	31.05	291	538		
				727	**1344**	%	**6%**

Table A-25 Bf-19 seventh level

bf-19	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.9 to E.9.5	4	30	31.05	291	538		
E.9.5 to E.10	6	30	31.05	436	806		
			Total	**727**	**1344**	%	**6%**

Table A-26 is for the 8th level with a story height 25 ft, *Kt* being 183 k/in, and *Wt* being 160.8 kips.

Table A-26 Bf-1 eighth level

bf-1	A (in^2)	L (ft)	Lbr (ft)	K (k/in)	W (k)	Node	W (k)
E.6 to E.6.5	2.5	30	39.05	91	80.4	83	80
E.6.5 to E.7	2.5	30	39.05	91	80.4	85	80
			Total	**183**	**160.8**	%	**100%**

A.3 BRB Force Demand-Capacity Ratios for Model 1

Table A-27 BRB Force demand-capacity ratios for Model 1

BRB ID	1.1 Ground Motion No Gravity	1.2 Ground Motion With Gravity	1.3 No Ground Motion With Gravity
11	0.95	0.95	0.05
12	1.06	1.08	0.08
15	1.05	1.05	0.08
16	1.06	1.08	0.08
21	0.94	0.96	0.06
22	1.02	1.01	0.07
25	1.03	1.06	0.09
26	1.02	1.01	0.07
31	1.50	1.50	0.03
33	1.37	1.38	0.11
34	1.39	1.40	0.15
35	1.37	1.38	0.11
36	1.39	1.40	0.15
41	0.43	0.43	0.02
42	0.54	0.54	0.03
43	0.80	0.83	0.12
44	0.79	0.80	0.10
45	0.80	0.83	0.12
46	0.79	0.80	0.10
47	0.80	0.83	0.12
48	0.79	0.80	0.10
49	0.80	0.83	0.12
410	0.79	0.80	0.10
51	1.47	1.47	0.04
52	1.52	1.52	0.07
53	1.42	1.41	0.08
54	1.42	1.42	0.08
55	1.01	1.01	0.03
56	1.10	1.09	0.04
63	0.80	0.80	0.02
64	0.80	0.80	0.01
65	0.74	0.74	0.03
66	0.75	0.74	0.04
67	0.74	0.74	0.03
68	0.75	0.74	0.04
73	0.12	0.12	0.01
74	0.12	0.12	0.01

A.4 BBB Force Demand-Capacity Ratios for Model 1 Ground Motion Simulations Scaled 2x

Table A-28 BRB force demand-capacity ratios for Model 1 ground motion simulations scaled 2x

BRB ID	1.1 Ground Motion No Gravity	1.2 Ground Motion With Gravity	1.3 No Ground Motion With Gravity
11	1.48	1.49	0.05
12	1.55	1.54	0.08
15	1.55	1.55	0.08
16	1.55	1.54	0.08
21	1.44	1.43	0.06
22	1.50	1.50	0.07
25	1.50	1.49	0.09
26	1.50	1.50	0.07
31	1.88	1.89	0.03
33	1.78	1.79	0.11
34	1.78	1.79	0.15
35	1.78	1.79	0.11
36	1.78	1.79	0.15
41	0.72	0.71	0.02
42	0.86	0.85	0.03
43	1.16	1.17	0.12
44	1.16	1.15	0.10
45	1.16	1.17	0.12
46	1.16	1.15	0.10
47	1.16	1.17	0.12
48	1.16	1.15	0.10
49	1.16	1.17	0.12
410	1.16	1.15	0.10
51	1.68	1.68	0.04
52	1.72	1.72	0.07
53	1.64	1.64	0.08
54	1.64	1.64	0.08
55	1.36	1.35	0.03
56	1.43	1.43	0.04
63	1.13	1.13	0.02
64	1.13	1.12	0.01
65	1.07	1.06	0.03
66	1.07	1.07	0.04
67	1.07	1.06	0.03
68	1.07	1.07	0.04
73	0.16	0.16	0.01
74	0.16	0.16	0.01

A.5 Model 2 Source Code

```
# -----------------------------------------------------------------------------------------------
# 3-Story EBRBF Test Frame
# Gary S. Prinz 2009
#
# nonlinear elements, inelastic fiber sections



# SET UP ----------------------------------------------------------------------------
wipe;                         # clear memory of all past model definitions
model BasicBuilder -ndm 2 -ndf 3;   #   Define   the   model   builder,
ndm=#dimension, ndf=#dofs
set dataDir EBRBF_Data;                 # set up name of data directory (can
remove this)
file mkdir $dataDir;                 # create data directory
set GMdir "../GMfiles/";                 # ground-motion file directory
source LibUnits.tcl;                 # define units
source DisplayPlane.tcl;             # procedure for displaying a plane in model
source DisplayModel2D.tcl;           # procedure for displaying 2D perspective of
model
source Wsection.tcl;           # procedure to define fiber W section
source rotSpring2D.tcl;              #  Rotational  spring  definition  for  beam
splices

# Analysis Type
        set Type "Dynamic"
                set EQ "LOMA-PRIETA_GILROY-3"
                set EQfact 1.4

#LOMA-PRIETA_GILROY-3   1.4
#LOMA-PRIETA_GILROY-4   1.4
#LOMA-PRIETA_HCH       1.2
#LOMA-PRIETA_HDA       0.93
#LOMA-PRIETA_S-CA      2.35



# define GEOMETRY -------------------------------------------------------------
# define NODAL COORDINATES
                node 1 0.0 0.0          # define nodes for EBRBF test frame
                node 2 0.0 156.0
                node 3 0.0 312.0
                node 4 0.0 468.0
                node 5 36.0 468.0
```

node 22 36.0 468.0
node 6 36.0 312.0
node 20 36.0 312.0
node 7 36.0 156.0
node 18 36.0 156.0
node 8 288.0 156.0
node 19 288.0 156.0
node 9 288.0 312.0
node 21 288.0 312.0
node 10 288.0 468.0
node 23 288.0 468.0
node 11 312.0 156.0
node 12 312.0 312.0
node 13 312.0 468.0
node 14 360.0 0.0
node 15 360.0 156.0
node 16 360.0 312.0
node 17 360.0 468.0

Set up parameters that are particular to the model for displacement control
set IDctrlNode 4; # node where displacement is read for displacement control
set IDctrlDOF 1; # degree of freedom of displacement read for displacement control
set NStory 3; # number of stories above ground level
set NBay 1; # number of bays
set LBuilding 468; # total building height

BOUNDARY CONDITIONS
fixY 0.0 1 1 1; # Fixed support nodes

calculated MODEL PARAMETERS, particular to this model

define MATERIAL properties --

Material properties, column and beam sections all defined in Input.tcl

$R0, $cR1, $cR2 control the transition from elastic to plastic branches.
Recommended values:
$R0=between 10 and 20, $cR1=0.925, $cR2=0.15
set R0_BC 20
set cR1_BC 0.925
set cR2_BC 0.15

Beam and Column Materials

```
set b_BC 0.01
set Fy 50
set Es 29000
set BCMat 10
uniaxialMaterial Steel02 $BCMat $Fy $Es $b_BC $R0_BC $cR1_BC $cR2_BC

# Brace Materials

set Fybrace 46
set BraceMat1 20000
set BraceMat2 30000
set b_Brace 0.025

# Parameters used in the Giuffré-Menegotto-Pinto equations
set R0_Brace 1.95;    # exponent that controls the transition between elastic and hardening branch
set cR1_Brace 0.001; # parameter for the change of R with cyclic loading history
set cR2_Brace 0.001; # parameter for the change of R with cyclic loading history

uniaxialMaterial Steel02 $BraceMat1 [expr $Fybrace*1.65] 62514 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace
uniaxialMaterial Steel02 $BraceMat2 [expr $Fybrace*1.65] 58398 $b_Brace $R0_Brace $cR1_Brace $cR2_Brace

# Rotational Spring Stiffness
#set SpringMat 100
#uniaxialMaterial Elastic $SpringMat 1000;   # E=10, essentially no rotational stiffness (pinned)

# puts "Materials Defined"

# ELEMENT properties --------------------------------------------------------------------
# Structural-Steel W-section properties

# column sections: W21x147
set ColSecTag 1
set d [expr 22.1*$in]; # depth
set bf [expr 12.5*$in];# flange width
set tf [expr 1.15*$in]; # flange thickness
set tw [expr 0.72*$in];        # web thickness
set nfdw 16;             # number of fibers along dw
set nftw 2;              # number of fibers along tw
```

```
set nfbf 16;		# number of fibers along bf
set nftf 4;			# number of fibers along tf
Wsection  1 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf

# beam sections: W27x102
#set BeamSecTag 2
set d [expr 27.1*$in];	# depth
set bf [expr 10*$in];	# flange width
set tf [expr 0.830*$in];		# flange thickness
set tw [expr 0.515*$in];		# web thickness
set nfdw 16;		# number of fibers along dw
set nftw 2;		# number of fibers along tw
set nfbf 16;		# number of fibers along bf
set nftf 4;			# number of fibers along tf
Wsection  2 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf

# beam sections: W24x103
#set BeamSecTag 3
set d [expr 24.5*$in];	# depth
set bf [expr 9.0*$in];	# flange width
set tf [expr 0.98*$in];	# flange thickness
set tw [expr 0.55*$in];		# web thickness
set nfdw 16;		# number of fibers along dw
set nftw 2;		# number of fibers along tw
set nfbf 16;		# number of fibers along bf
set nftf 4;			# number of fibers along tf
Wsection  3 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf

# beam sections: W21x68
#set BeamSecTag 3
set d [expr 21.1*$in];	# depth
set bf [expr 8.27*$in];# flange width
set tf [expr 0.685*$in];		# flange thickness
set tw [expr 0.430*$in];		# web thickness
set nfdw 16;		# number of fibers along dw
set nftw 2;		# number of fibers along tw
set nfbf 16;		# number of fibers along bf
set nftf 4;			# number of fibers along tf
Wsection  4 $BCMat $d $bf $tf $tw $nfdw $nftw $nfbf $nftf


# define ELEMENTS ----------------------------------------------------------------------
## element nonlinearBeamColumn $elemID $nodeI $nodeJ $np $ColSecTag $IDColTransf;
# set up geometric transformations of element
#   separate columns and beams, in case of P-Delta analysis for columns
```

```
set IDColTransf 101; # all columns
set IDBeamTransf 102; # all beams
set IDBraceTransf 103; # all braces
set ColTransfType Corotational;             # options, Linear PDelta Corotational
geomTransf $ColTransfType $IDColTransf ;    # only columns can have PDelta effects (gravity effects)
geomTransf Corotational $IDBeamTransf
geomTransf Corotational $IDBraceTransf

set np 5;    # number of Gauss integration points for nonlinear curvature distribution

# COLUMNS
	element nonlinearBeamColumn 1 1 2 $np 1 $IDColTransf;
	element nonlinearBeamColumn 2 2 3 $np 1 $IDColTransf;
	element nonlinearBeamColumn 3 3 4 $np 1 $IDColTransf;
	element nonlinearBeamColumn 5 14 15 $np 1 $IDColTransf;
	element nonlinearBeamColumn 6 15 16 $np 1 $IDColTransf;
	element nonlinearBeamColumn 7 16 17 $np 1 $IDColTransf;

# BEAMS
	element nonlinearBeamColumn 8 2 7 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 9 18 8 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 10 19 11 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 20 11 15 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 11 3 6 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 12 20 9 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 13 21 12 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 21 12 16 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 14 4 5 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 15 22 10 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 16 23 13 $np 3 $IDBeamTransf;
	element nonlinearBeamColumn 22 13 17 $np 3 $IDBeamTransf;

# BRACES
	element corotTruss 17 1 11 [expr 6.77*pow($in,2)] $BraceMat1;
	element corotTruss 18 2 12 [expr 5.895*pow($in,2)] $BraceMat1;
	element corotTruss 19 3 13 [expr 4.518*pow($in,2)] $BraceMat1;

	# Perfectly Pinned Splice
		equalDOF 7 18 1 2
		equalDOF 8 19 1 2
		equalDOF 6 20 1 2
		equalDOF 9 21 1 2
		equalDOF 5 22 1 2
```

```
equalDOF 10 23 1 2

# Assign masses to nodes
    mass 2 1.02375 1e-9 1e-9
    mass 15 1.02375 1e-9 1e-9
    mass 3 1.02375 1e-9 1e-9
    mass 16 1.02375 1e-9 1e-9
    mass 4 1.1078 1e-9 1e-9
    mass 17 1.1078 1e-9 1e-9

# Rigid Diaphragm; Forces the horizontal displacement of column nodes to be equal
    equalDOF 2 15 1
    equalDOF 3 16 1
    equalDOF 4 17 1

# define GRAVITY -------------------------------------------------------------

set WzBeam 0.158;
pattern Plain 1 Linear {
eleLoad -ele 8 -type -beamUniform -$WzBeam ; # distributed load on beam
eleLoad -ele 9 -type -beamUniform -$WzBeam ; # distributed load on beam
eleLoad -ele 10 -type -beamUniform -$WzBeam ; # distributed load on beam
eleLoad -ele 20 -type -beamUniform -$WzBeam ; # distributed load on beam

eleLoad -ele 11 -type -beamUniform -$WzBeam ; # distributed load on beam
eleLoad -ele 12 -type -beamUniform -$WzBeam ; # distributed load on beam
eleLoad -ele 13 -type -beamUniform -$WzBeam ; # distributed load on beam
eleLoad -ele 21 -type -beamUniform -$WzBeam ; # distributed load on beam

eleLoad -ele 14 -type -beamUniform -$WzBeam ; # distributed load on beam
eleLoad -ele 15 -type -beamUniform -$WzBeam ; # distributed load on beam
eleLoad -ele 16 -type -beamUniform -$WzBeam ; # distributed load on beam
eleLoad -ele 22 -type -beamUniform -$WzBeam ; # distributed load on beam
}

# ------------------------------------------------- apply gravity load
set Tol 1.0e-8;            # convergence tolerance for test
constraints Plain;         # how it handles boundary conditions
numberer Plain;            # renumber dof's to minimize band-width (optimization), if you want to
system BandGeneral;        # how to store and solve the system of equations in the analysis
test NormDispIncr $Tol 6 ; # determine if convergence has been achieved at the end of an iteration step
```

algorithm Newton; # use Newton's solution algorithm: updates tangent stiffness at every iteration
set NstepGravity 10; # apply gravity in 10 steps
set DGravity [expr 1./$NstepGravity]; # first load increment;
integrator LoadControl $DGravity; # determine the next time step for an analysis
analysis Static; # define type of analysis static or transient
analyze $NstepGravity; # apply gravity
-- maintain constant gravity loads and reset time to zero
loadConst -time 0.0

Story Drifts
recorder Drift -file $dataDir/$Type/$EQ/Drift_EBRBF_EQ.out -time -iNode 1 2 3 -jNode 2 3 4 -dof 1 -perpDirn 2; # drift story

Brace Hysteresis
recorder Element -file $dataDir/$Type/$EQ/Axial_EBRBF_EQ.out -time -ele 17 18 19 axialForce; # Brace 1 Axial Force
recorder Element -file $dataDir/$Type/$EQ/Deform_EBRBF_EQ.out -time -ele 17 18 19 deformations; # Brace 1 Axial Force

Node and Element Recorders
Nodal Displacements and Accelerations
recorder Node -file $dataDir/$Type/$EQ/NodeDisp_EBRBF_EQ.out -time -node 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 -dof 1 2 disp; # Nodal displacements
recorder Node -file $dataDir/$Type/$EQ/NodeDispStaticPush_EBRBF_EQ.out -time -node 4 -dof 1 disp;
Nodal displacements
recorder Node -file $dataDir/$Type/$EQ/NodeAccel_EBRBF_EQ.out -time -node 2 15 3 16 4 17 -dof 1 2 3 accel; # Nodal Accel

recorder Element -file $dataDir/$Type/$EQ/LinkForce_EBRBF_EQ.out -time -ele 20 21 22 localForce;
recorder Element -file $dataDir/$Type/$EQ/BeamForce_EBRBF_EQ.out -time -ele 8 11 14 localForce;

#DisplayModel2D NodeNumbers

```
# ------------ PeriodFreq&Damping -------------------------------------
# determine Natural Period, Frequency & damping parameters for SDOF

set xDamp 0.05; # damping ratio (0.02-0.05-typical)
set lambda [eigen 1]
set omega [expr pow($lambda,0.5)]
set Tperiod [expr 2*$PI/$omega]; # period (sec.)
puts $Tperiod
set alphaM 0; # stiffness-prop. RAYLEIGH damping parameter; D = alphaM*M
set betaK 0; # stiffness proportional damping; +betaK*KCurrent
set betaKcomm [expr 2*$xDamp/$omega]; # mass-prop. RAYLEIGH damping parameter; +betaKcomm*KlastCommitt
set betaKinit 0; # initial-stiffness proportional damping +beatKinit*Kini
```