CHAPTER 5

1:6-Scale Frame: Northridge Ground-Motion Modeling and Testing

5.1 Overview

This Chapter was organized with the intent of concisely presenting pertinent aspects of analytical and experimental results for the 1:6-scale shaking table experiments using Northridge ground-motion input, and reporting on the effectiveness of the ropes in improving performance of the 1:6-scale frame. The results of DRAIN simulations used to estimate the response of the 1:6-scale frame with and without the rope devices subject to planned Northridge ground-motion input are presented in Section 5.2. The details of the shaking table experiment are presented in Section 5.3. Results for tests conducted on Frame 1, tested without ropes, are presented in Section 5.4 with comparison to the corresponding DRAIN analyses. Results for tests conducted on Frame 2, tested with ropes, are presented in Section 5.5 with comparison to the corresponding DRAIN analysis. Since comparison of the analytical model with experimental results was of interest to the study, commentary on the accuracy of the analytical model for predicting the response of the 1:6-scale frame is also provided in Sections 5.4 and 5.5. An evaluation of the DRAIN model is presented in Section 5.6. Direct comparison of the results from Frame 1 and Frame 2 tests is presented in Section 5.7. Commentary on experimental performance of the ropes and a summary of experimental findings are presented in Sections 5.8 and 5.9, respectively.

Table 5.1 lists the tests conducted on the shaking table with Northridge ground-motion input. Test designations are presented in the first column. Included in the designation are three hyphen-delimited elements, ground motion (NR-Northridge), frame (1 or 2), and the scaling percentage of the acceleration history (30%, 180%, or 220%). Test date and use of ropes is also indicated for clarity. These designations are referenced throughout and are relevant to analytical DRAIN results as well as experimental tests.

5.2 DRAIN Modeling

A nonlinear finite element model was developed in Chapter 4 using DRAIN for various purposes. Specifically, the purpose of finite-element modeling, as it relates to the 1:6-scale shaking table tests, was to model the test results as closely as possible including the incorporation of an element developed to model the rope response. The ultimate goal was to predict the response of the frame without ropes and then the change to the frame response after ropes were introduced to the system. A general diagram of the complete DRAIN model used for all simulations reported in this chapter is shown in Chapter 4, Figure 4.17. Using the DRAIN model, simulations were performed that correspond to the shaking-table tests NR-1-30, NR-2-30, NR-1-180, and NR-2-180. Because Tests NR-1-220 and NR-2-220 were conducted for the purpose of determining repeatability of results observed in Tests NR-1-180 and NR-2-180, analytical DRAIN simulations of these tests were not conducted. Results for each test are presented in Sections 5.2.1 through 5.2.4.

Table 5. 1: Northridge Ground Motion Test Designations

Test Designation	Frame	Rope Condition	% Northridge Ground Motion	Experimental Test Date
NR-1-30	Frame 1	No Ropes	30%	21-JUN-06
NR-1-180	Frame 1	No Ropes	180%	21-JUN-06
NR-1-220	Frame 1	No Ropes	220%	21-JUN-06
NR-2-30	Frame 2	with Ropes	30%	05-AUG-06
NR-2-180	Frame 2	with Ropes	180%	05-AUG-06
NR-2-220	Frame 2	with Ropes	220%	05-AUG-06

For improved accuracy of the analytical results, the rope model in DRAIN, developed in Chapter 3, was adapted to the actual response of 0.25-in.-diameter ropes used in the shaking table tests, measured during rope conditioning. The ropes were cycled twice between 0 and approximately 3,000 lb. The measured responses for the North-Bottom rope and the South-Top rope used in the shaking-table experiments are shown in Figure 5.1. The response of the DRAIN Type-09 element model used to model all ropes is also shown for comparison. The DRAIN response output for the Type-09 element was taken from the simulation of Test NR-2-180.

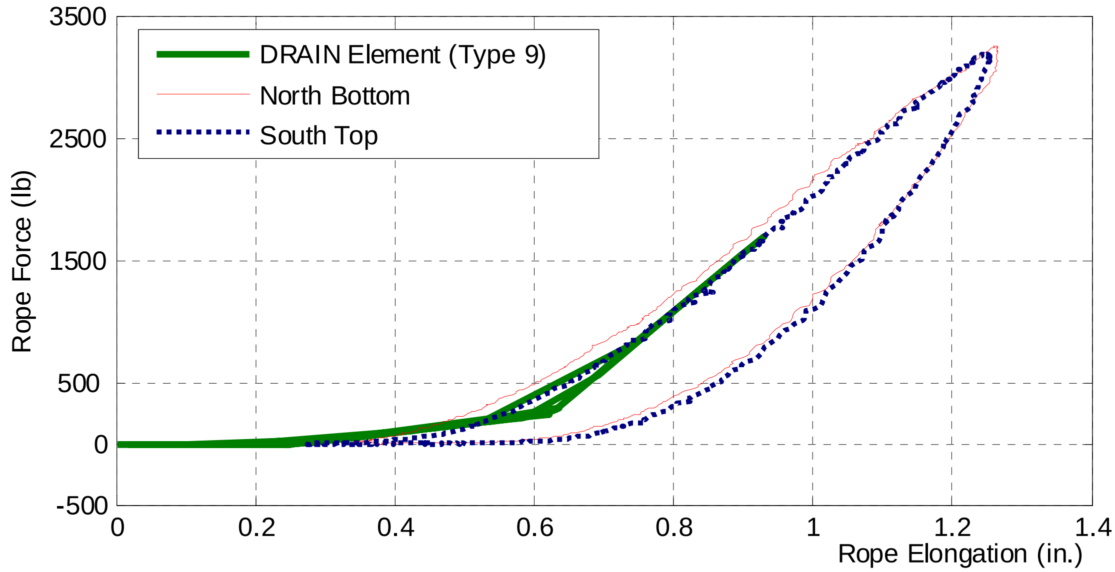


Figure 5. 1: DRAIN Rope Element Response vs. 0.25-in. Rope Response

5.2.1 DRAIN MODELING SIMULATING TEST NR-1-30

The Northridge acceleration record was reduced to 30% of the full-scale recorded value for the DRAIN simulations used to estimate the response of Test NR-1-30 (30% Northridge ground motion, Frame 1, No Ropes). To maintain proper similitude, the time increment used for the simulation, 0.00832 sec, was determined by dividing the time increment of the full-scale record, 0.02 sec, by the square root of the length scale factor of the scale model. Diaphragm-level displacement, acceleration, and total base shear were of interest. Resulting roof and floor displacements with respect to time are shown in Figure 5.2, roof and floor level accelerations are shown in Figure 5.3, and total base shear is shown in Figure 5.4.

The purpose of simulating NR-1-30 was two-fold. Since the NR-1-30 experiment would be used to verify proper performance of the shaking-table equipment and the method employed to generate the intended command signal, it was important to verify that the moment frame would not be driven into the inelastic range when subjected to low-level excitation corresponding to 30% of the Northridge ground motion. By incrementing the level of Northridge ground motion input in a series of DRAIN simulations, the threshold of yielding in the frame was estimated to occur at approximately 60% of the Northridge ground motion. The 30% level was therefore considered to be well below that threshold, while allowing for adequate response for obtaining meaningful accelerometer readings for the second objective, experimental verification of the model at low-level ground-motion excitation. It was important to verify the accuracy of the analytical model at lower ground-motion excitation levels to demonstrate that the accuracy of the simulation with higher ground-motion excitation levels was not anomalous. Commentary on the accuracy of the DRAIN model with respect to experimental results is provided with the presentation of the experimental results of NR-1-30, reported in Section 5.4.1.

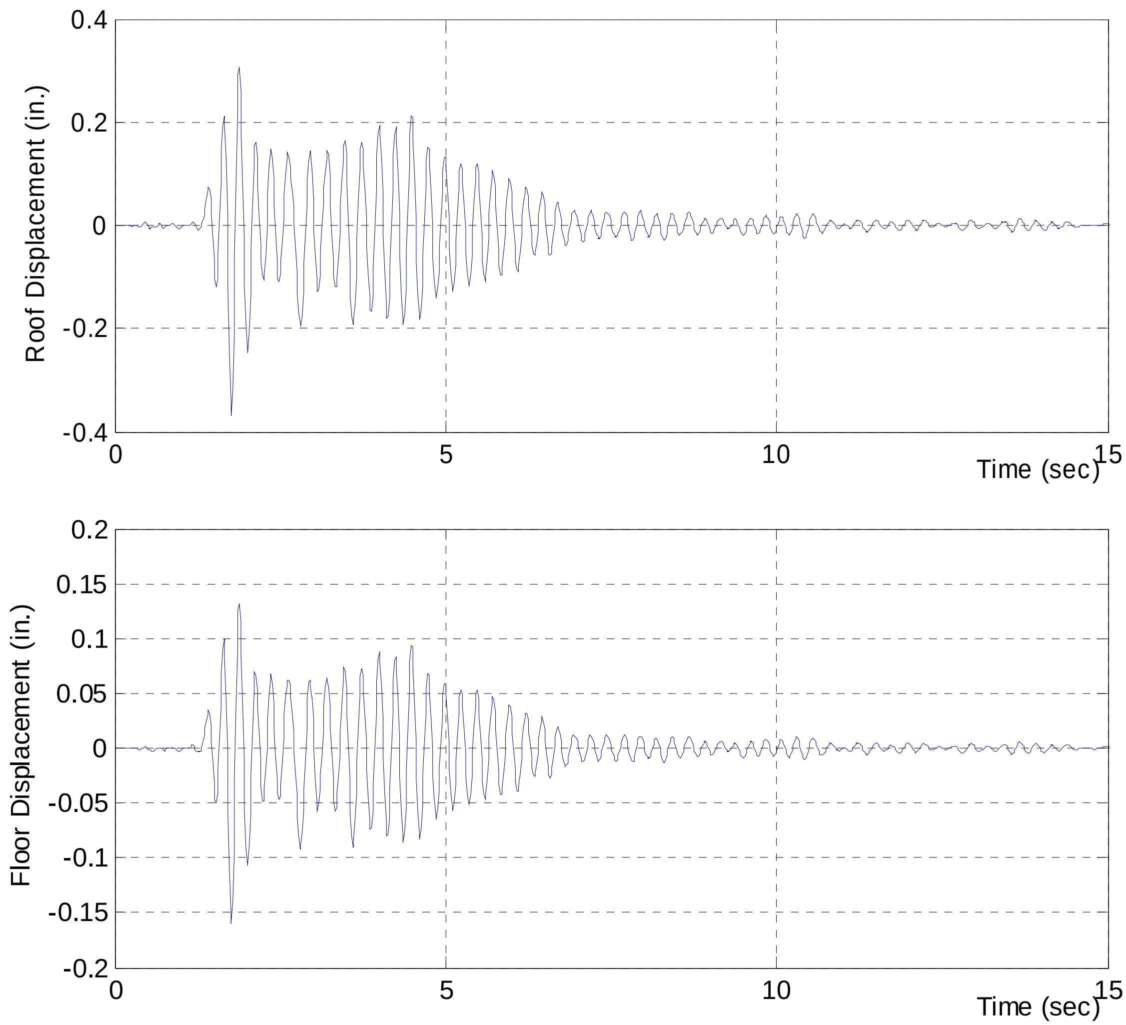


Figure 5. 2: DRAIN Roof and Floor Displacements: NR-1-30

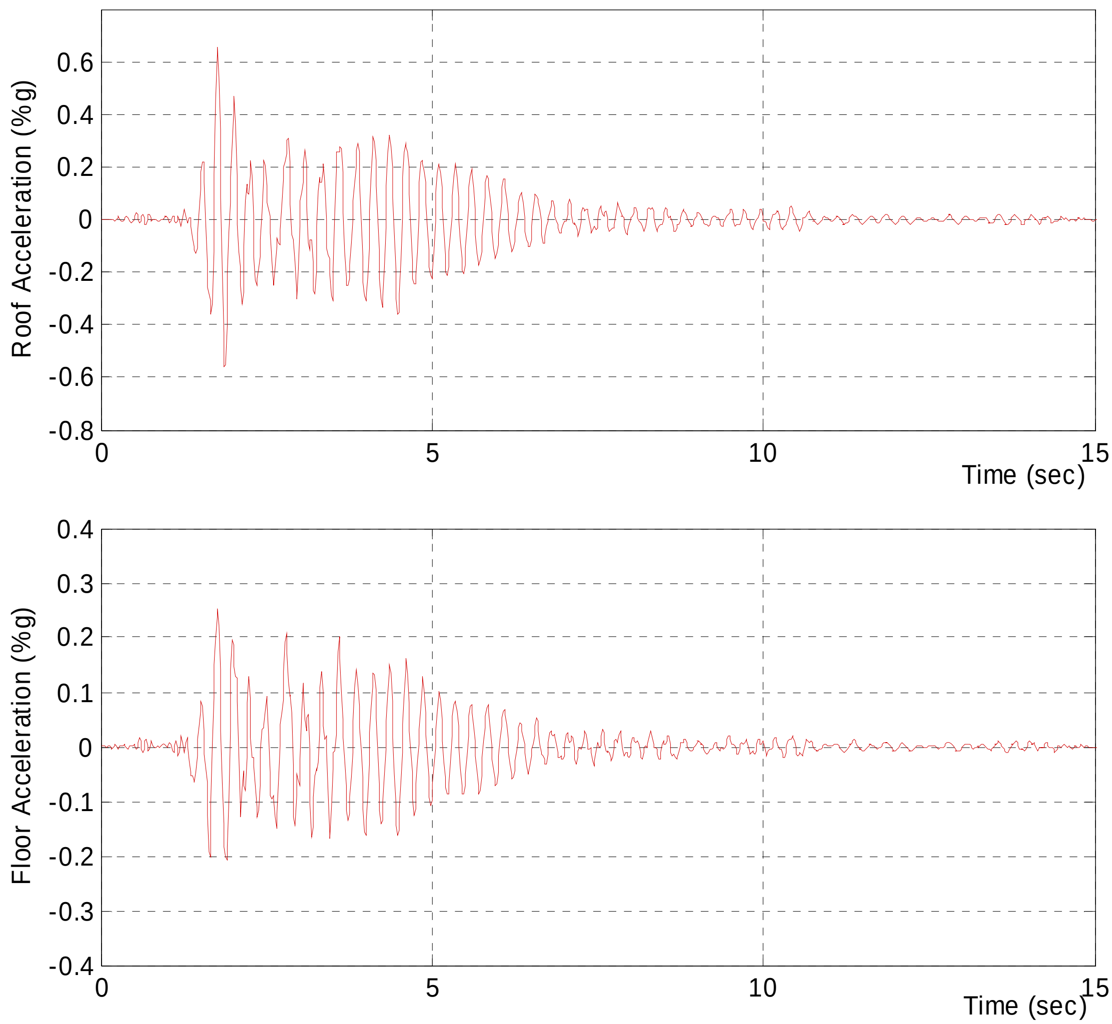


Figure 5. 3: DRAIN Roof and Floor Accelerations: NR-1-30

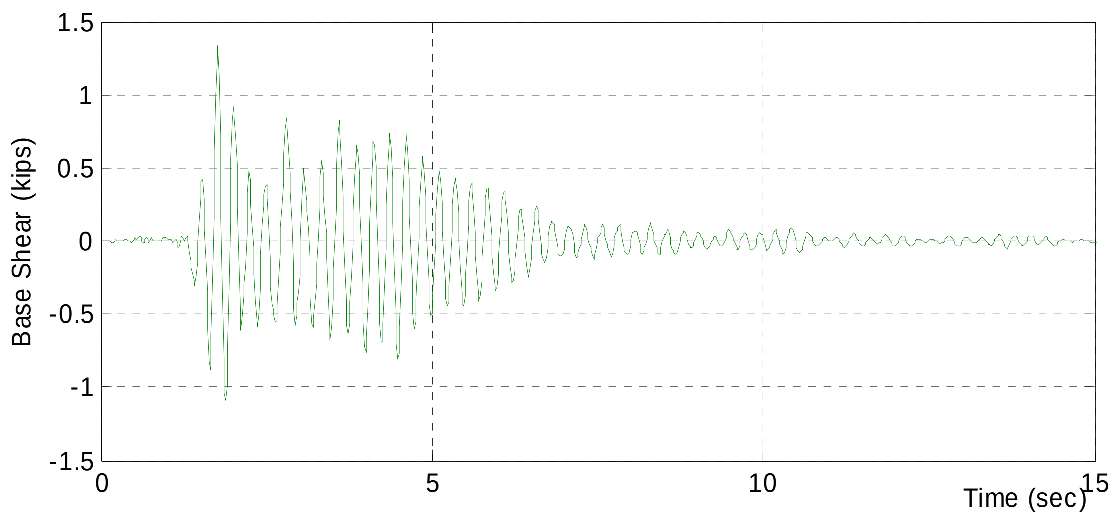
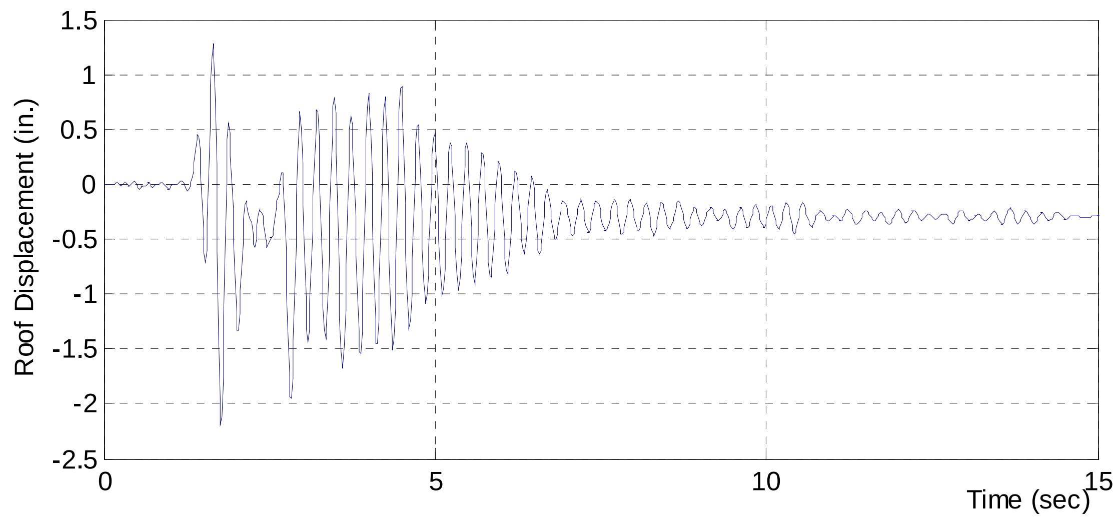


Figure 5. 4: DRAIN Base Shear: NR-1-30

5.2.2 DRAIN Modeling Simulating Test NR-1-180

The Northridge acceleration record was increased to 180% of full-scale value for DRAIN simulations used to estimate the response of Test NR-1-180 (180% Northridge ground motion, Frame 1, No Ropes). The adjustment of the time increment between acceleration values was conducted as previously stated. Diaphragm-level displacement, acceleration, and total base shear were of interest. Resulting roof and floor displacements with respect to time are shown in Figure 5.5, roof and floor level accelerations are shown in Figure 5.6, and total base shear is shown in Figure 5.7.



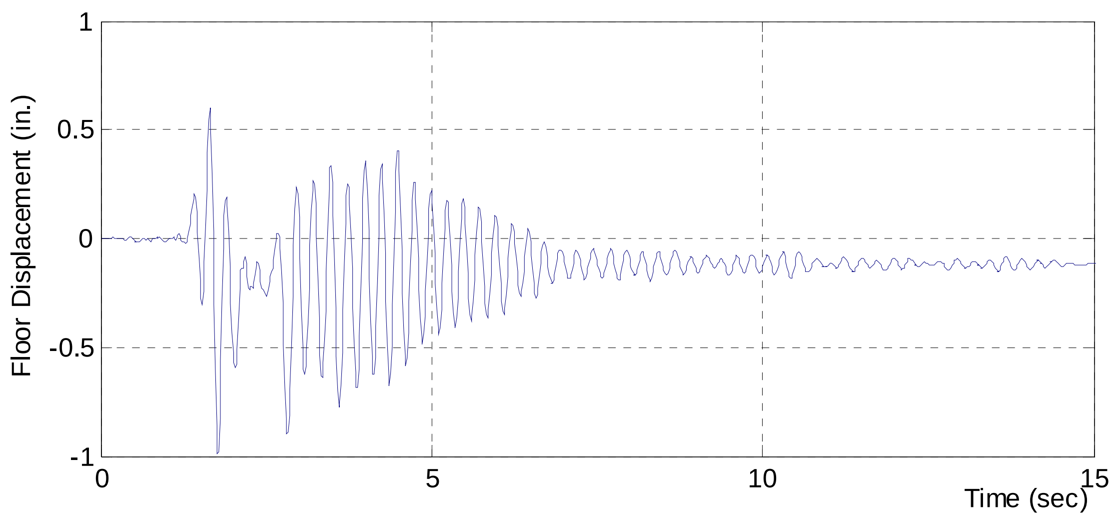


Figure 5. 5: DRAIN Roof and Floor Displacements: NR-1-180

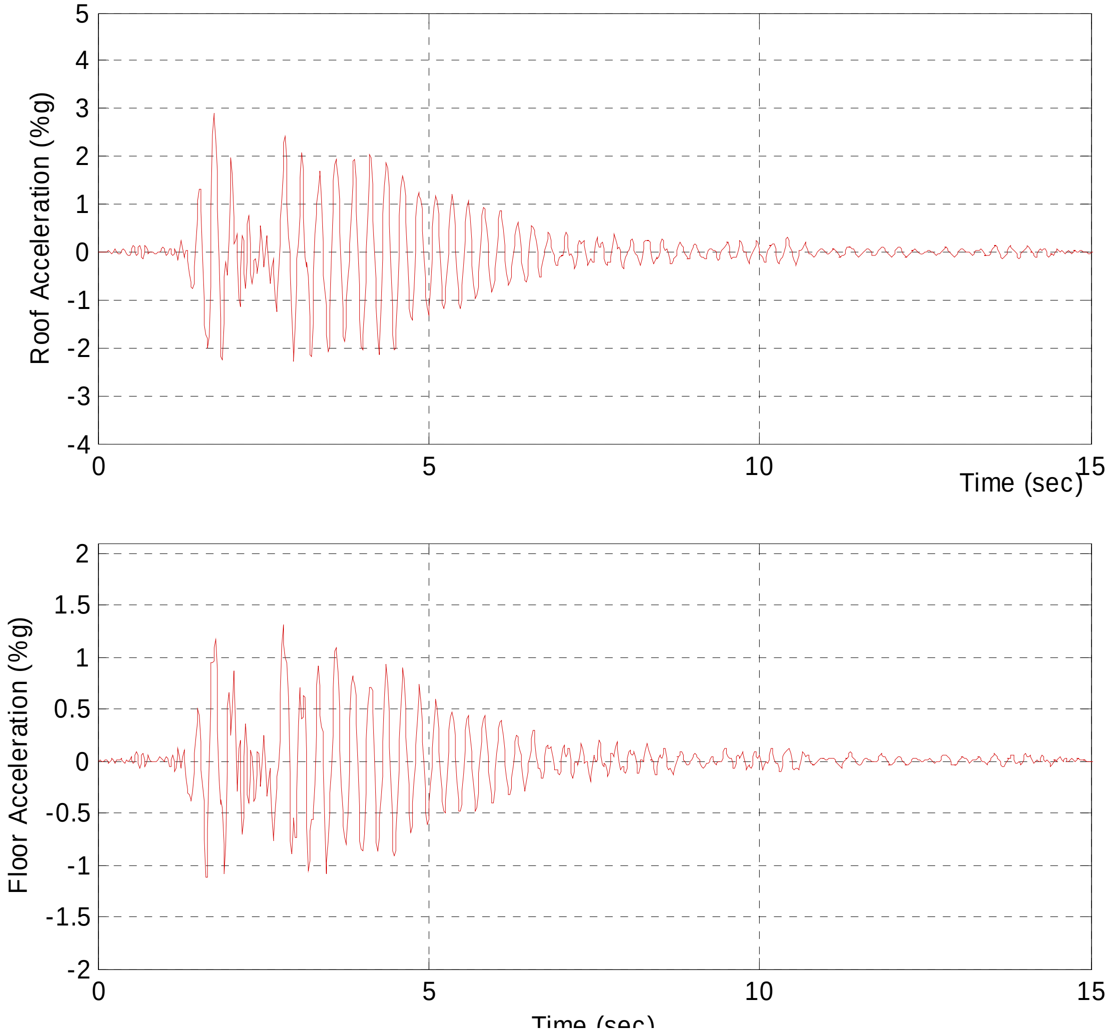


Figure 5. 6: DRAIN Roof and Floor Accelerations: NR-1-180

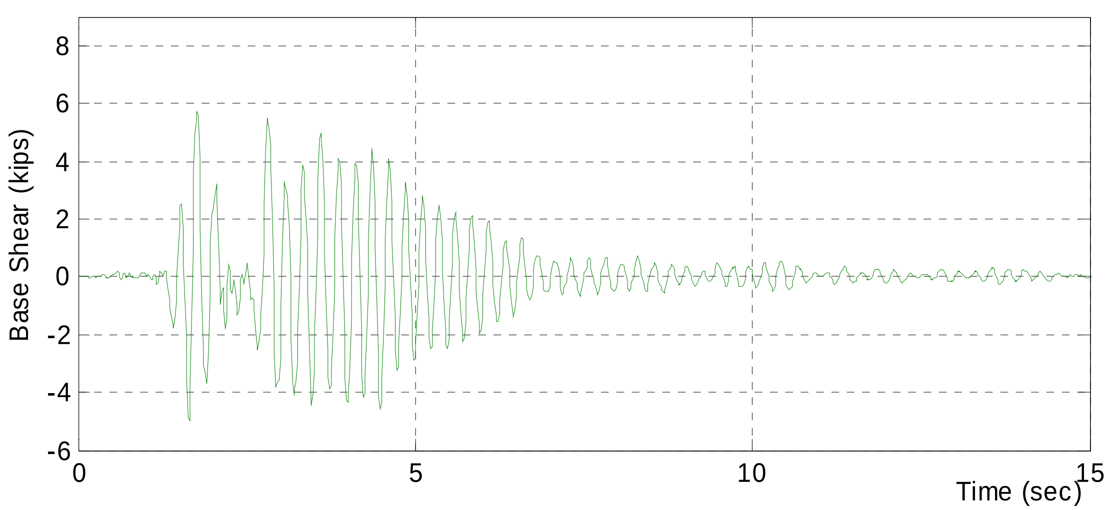


Figure 5. 7: DRAIN Base Shear: NR-1-180

The purpose for simulating Test NR-1-180 was to estimate experimental results. One objective of the 180%-Northridge tests was to demonstrate the mitigation of residual drift by the ropes. Therefore, the Northridge ground-motion level that would result in significant residual deformation without inducing collapse was required. The DRAIN simulation of Test NR-1-180 estimated residual roof drift and residual floor drift to be equal to 0.28 in. and 0.15 in. respectively. It was determined that these values could be measured reliably after the NR-1-180 experiment. Maximum roof and floor drift were predicted to be 2.2 in. and 0.98 in. respectively. Bending moments in the frame members, including second-order moments, due to maximum drift were determined based on static conditions. Based on the static condition of the frame with estimated displacements and ballast loads, it was determined that the 180%-Northridge ground motion would not result in collapse.

In addition, the primary basis of comparison for experimental frame performance with and without the ropes was the results from Test NR-1-180 versus results from Test NR-2-180. Therefore, it was important to verify the DRAIN model results at the 180% excitation level. Commentary on the accuracy of the model with respect to experimental results is provided with the presentation of the experimental results of NR-1-180 and NR-2-180 in Sections 5.4.2 and 5.4.4, respectively.

5.2.3 DRAIN MODELING SIMULATING TEST NR-2-30

The Northridge acceleration record was increased to 30% of full-scale value for DRAIN simulations used to estimate the response of Test NR-2-30 (30% Northridge ground motion, Frame 1, with Ropes) Rope elements were added based on experimental values obtained for ropes to be used in the 1:6-scale frame experiment as described in Section 5.2. The time increment was adjusted as previously stated. Diaphragm-level displacement, acceleration, and total base shear were of interest. Resulting roof and floor displacements with respect to time are shown in Figure 5.8, roof and floor level accelerations are shown in Figure 5.9, and total base shear is shown in Figure 5.10. Rope forces calculated in DRAIN are shown in Figure 5.11 for the four ropes.

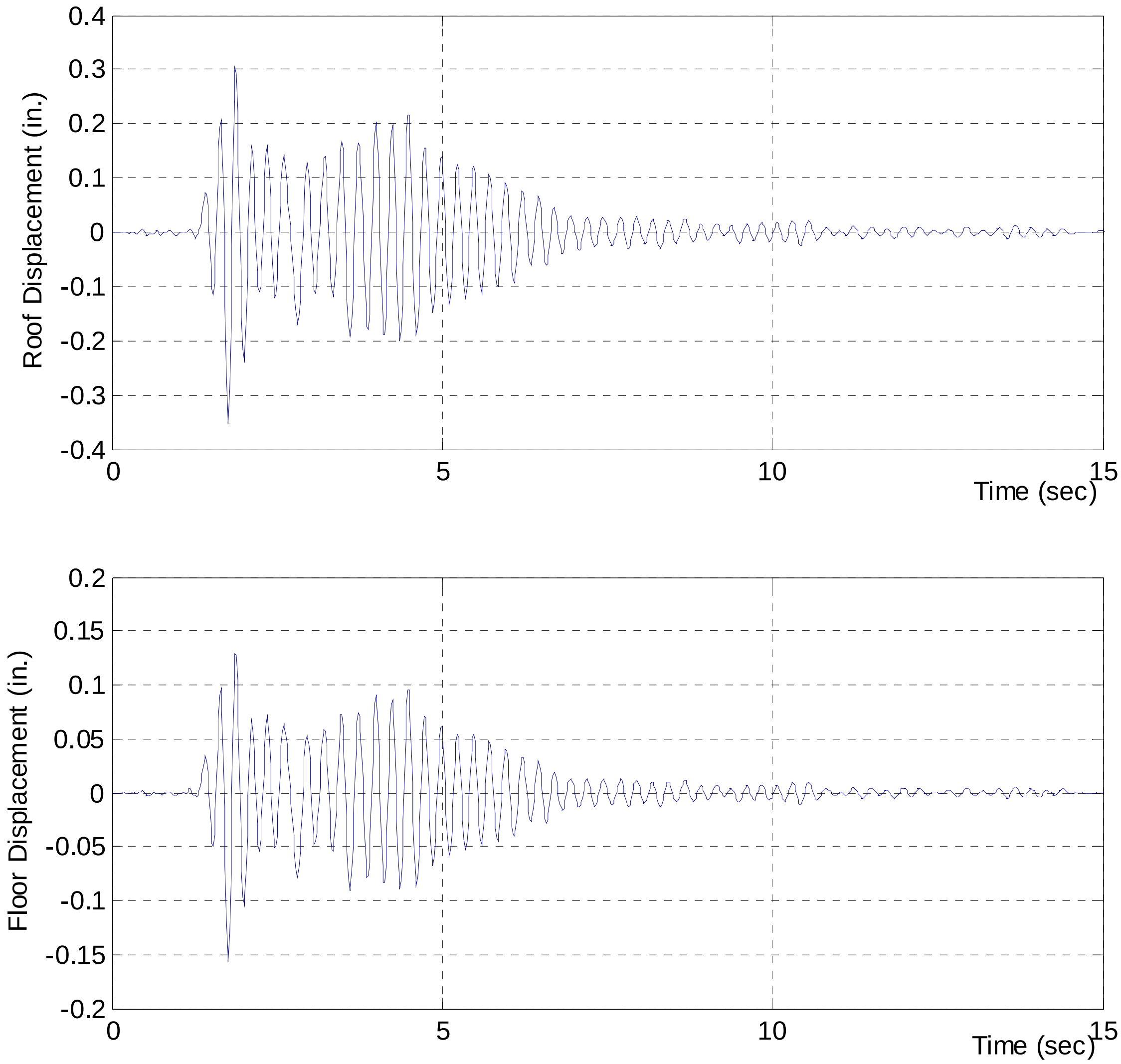


Figure 5. 8: DRAIN Roof and Floor Displacements: NR-2-30

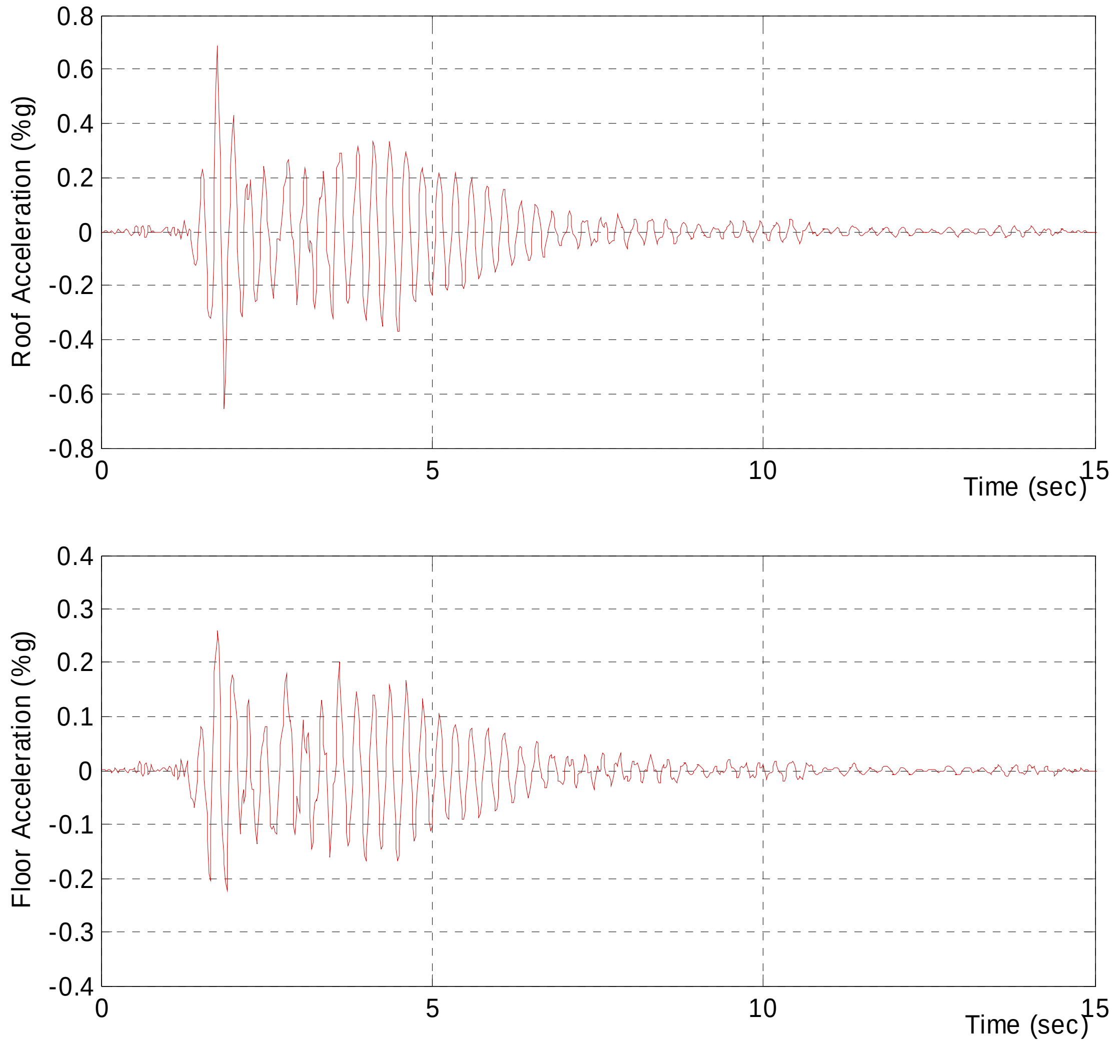


Figure 5. 9: DRAIN Roof and Floor Accelerations: NR-2-30

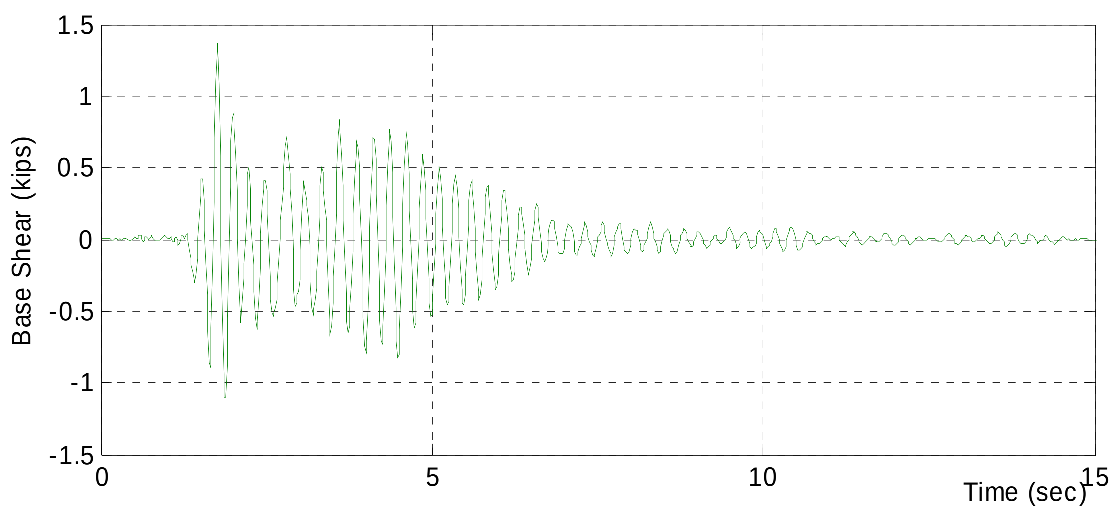


Figure 5. 10: DRAIN Base Shear: NR-2-30

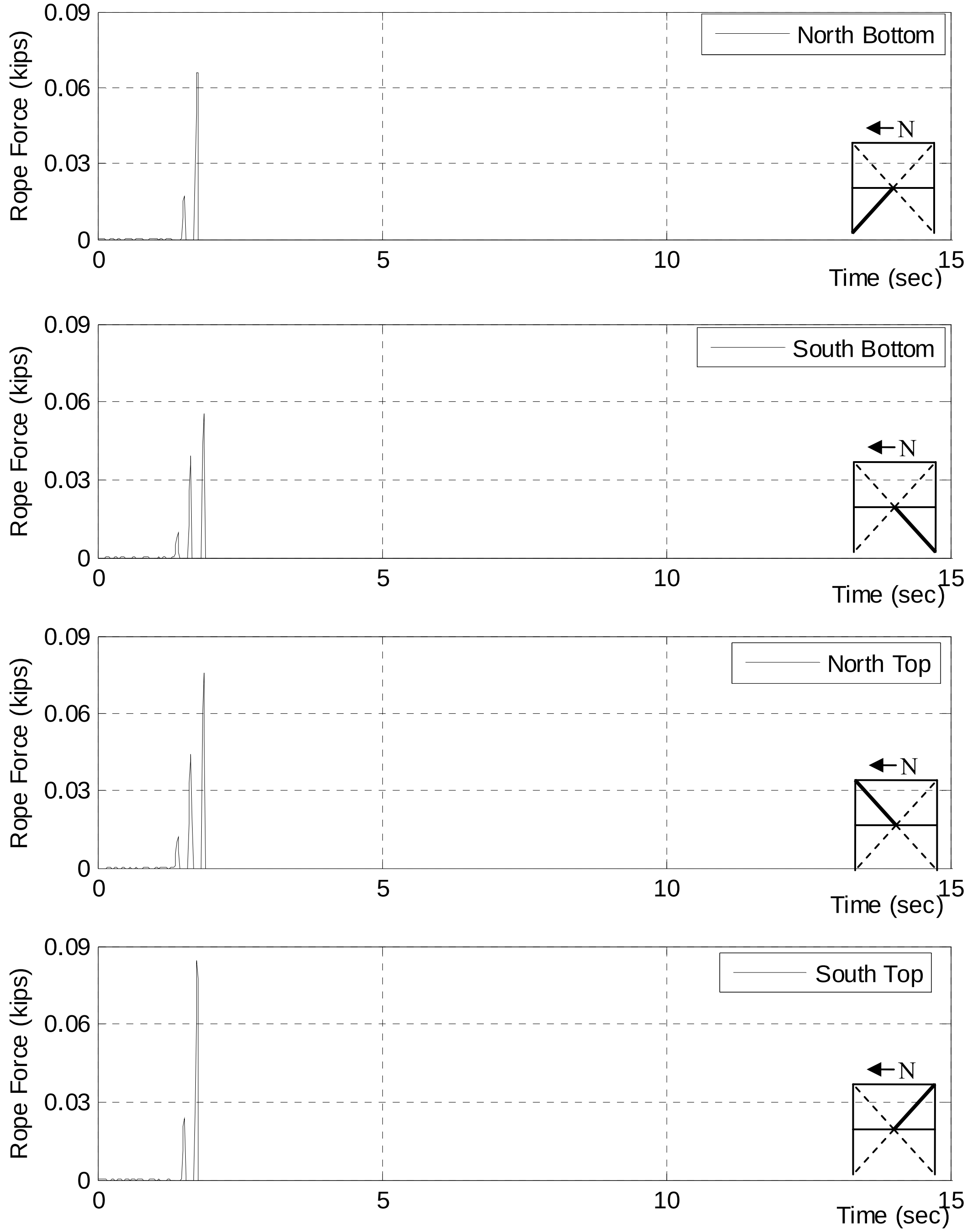


Figure 5. 11: DRAIN Rope Forces

5.2.4 DRAIN MODELING SIMULATING TEST NR-2-180

The Northridge acceleration record was increased to 180% of full-scale value for DRAIN simulations used to estimate the response of Test NR-2-180 (180% Northridge ground motion, Frame 1, with Ropes). Rope elements were added and the time increment was set to 0.00832 sec as previously stated. Resulting roof and floor displacements with respect to time are shown in Figure 5.12, roof and floor level accelerations are shown in Figure 5.13, and total base shear is shown in Figure 5.14. Rope forces calculated in DRAIN are shown in Figure 5.15 for all ropes.

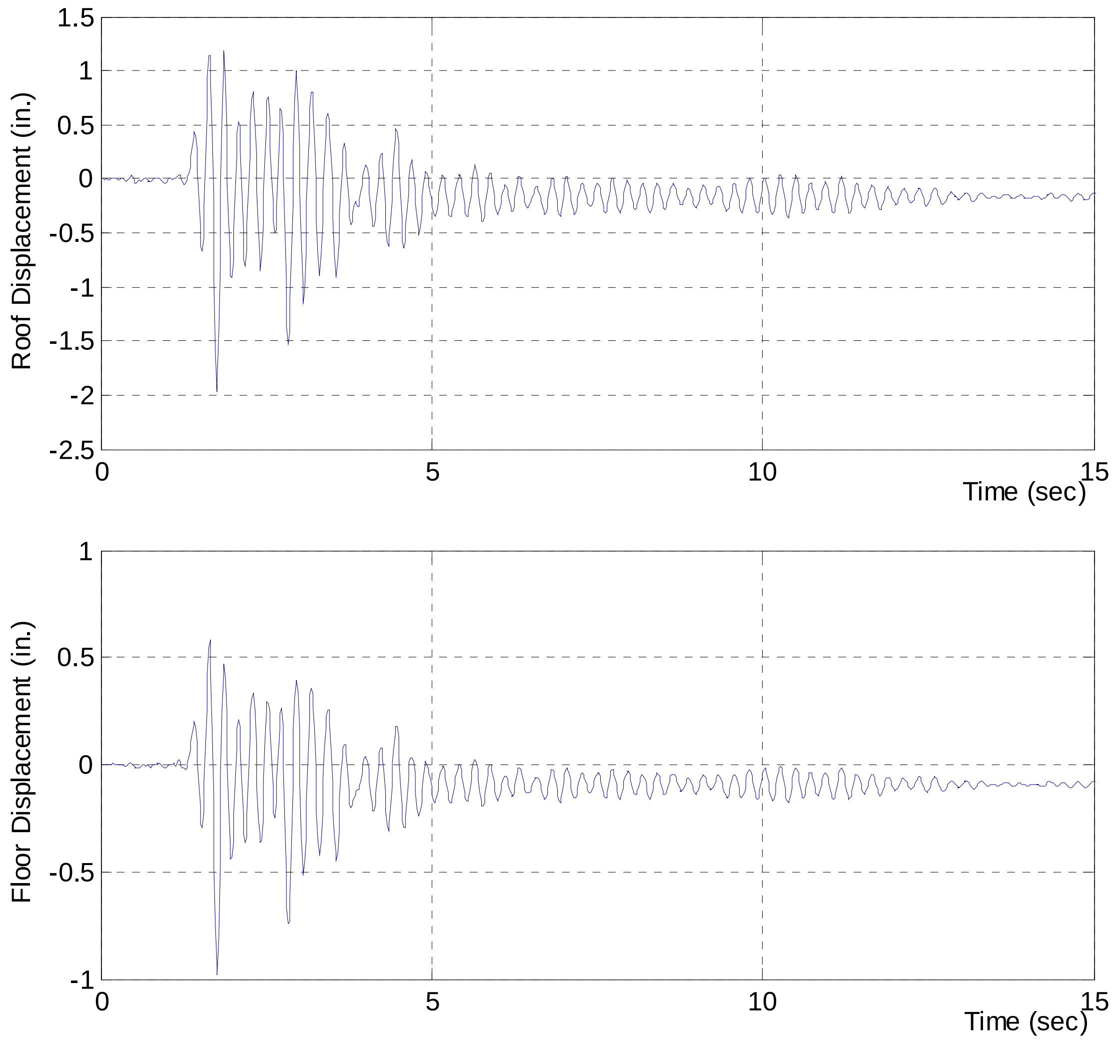


Figure 5. 12: DRAIN Roof and Floor Displacements: NR-2-180

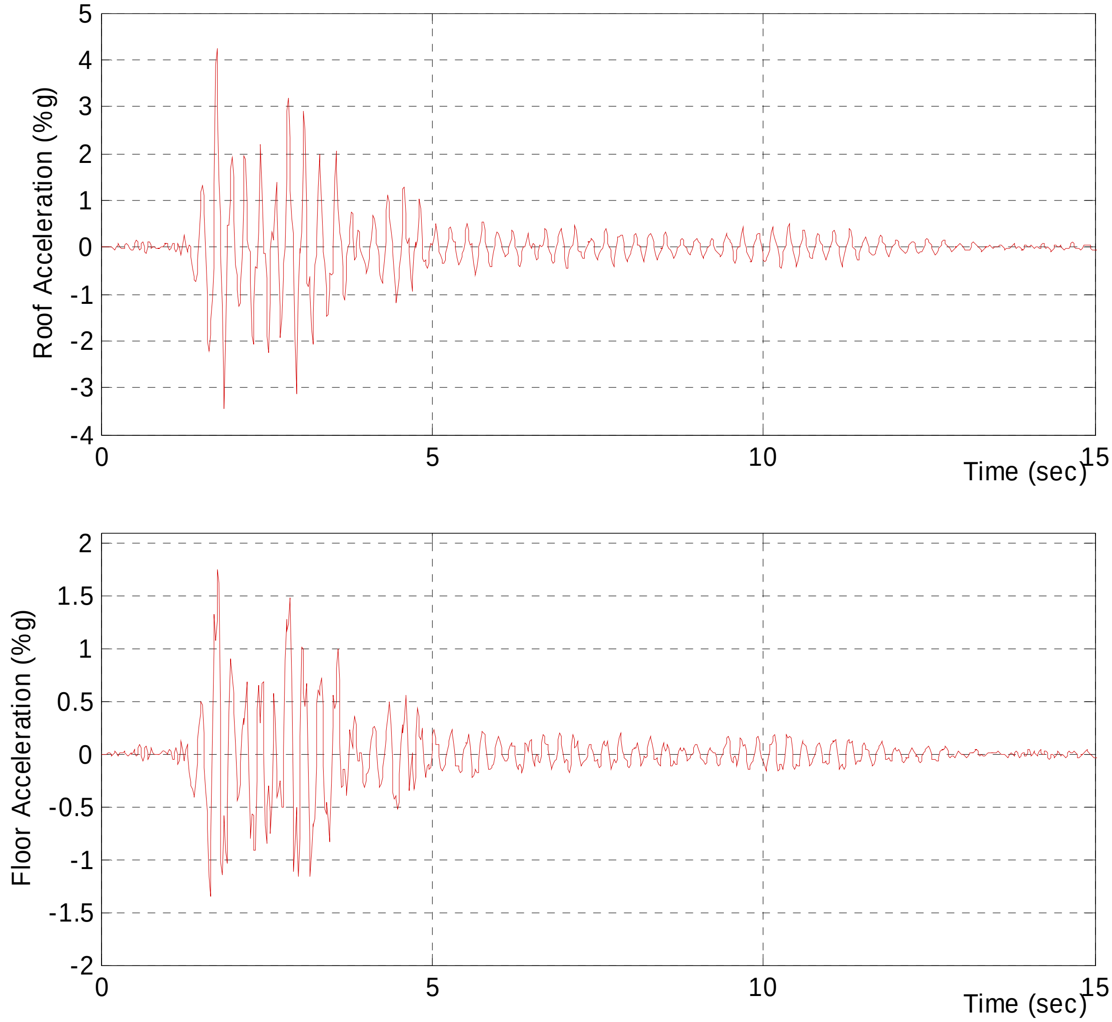


Figure 5. 13: DRAIN Roof and Floor Accelerations: NR-2-180

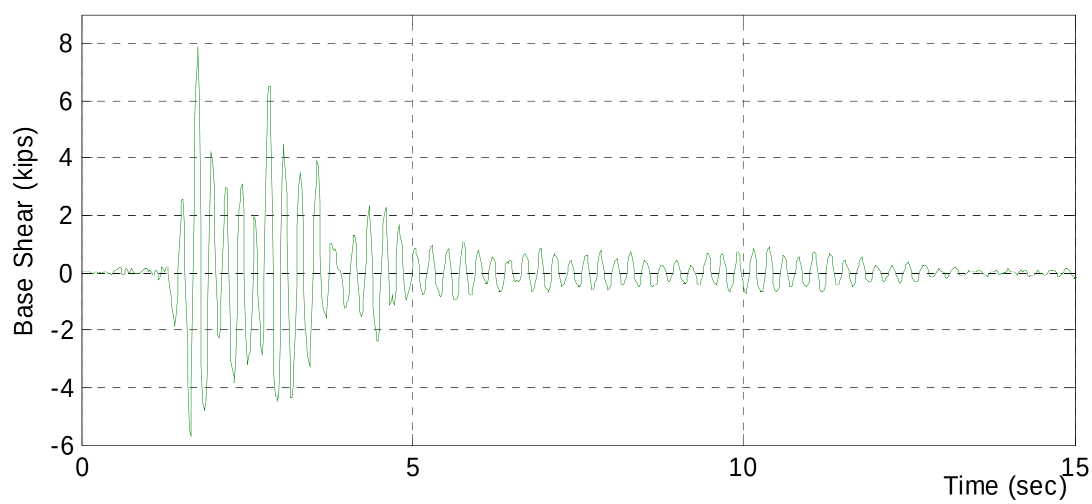


Figure 5. 14: DRAIN Base Shear: NR-2-180

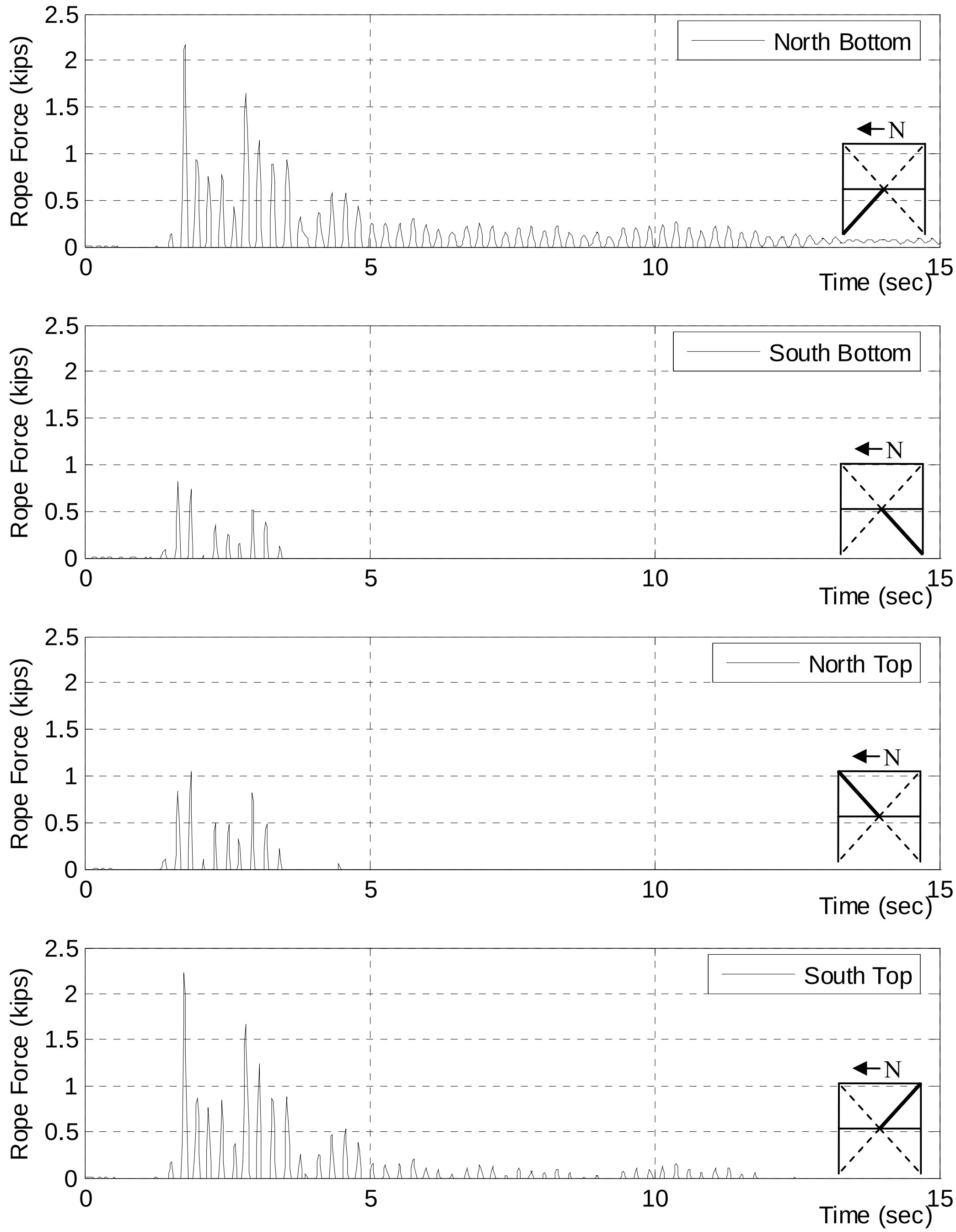


Figure 5. 15: DRAIN Rope Forces

5.3 DESCRIPTION OF SHAKING-TABLE TEST SET-UP

A complete description of the moment frames and leaner frame design and fabrication are presented in detail in Chapter 4. Chapter 4 also details the method for measuring and recording acceleration at the diaphragm levels of the experimental frame during modal testing. Several aspects of the shaking-table experiment were specific to the tests with Northridge ground-motion input, and not pertinent to the tests described in Chapter 4. These aspects are described herein and include instrumentation and data acquisition related to measuring and recording strain of the frame and tension in the ropes, addition of brackets and gusset plates to Frame 2 for the purpose of making rope connections, the addition of input devices required for the purpose of actuator control related to Northridge ground-motion input, and the measurement of residual deformation for 180% and 220% Northridge ground-motion tests.

5.3.1 INSTRUMENTATION AND DATA ACQUISITION

A diagram of all instrumentation used for the Northridge ground-motion tests is provided in Figure 5.16. Locations and instrument designations are indicated. These designations are used to identify test results throughout this Chapter.

Instrumentation and data acquisition for the Northridge ground-motion tests were similar to those of the modal testing with some additions. Acceleration data was measured at the roof, floor, and shaking table levels and recorded using the four-channel Sig-lab unit as described in Chapter 4. A direct position feedback voltage signal from the LVDT, internal to the shaking-table actuator, was monitored through the Schenk controller and synchronized with accelerometer data as described in Chapter 4.

Data recorded during ground-motion testing that was not recorded during modal testing included moment-frame strain and tension in the ropes. Maximum bending strains of the beams were monitored using 120-Ohm uni-axial strain gages. The gages were installed at the top and bottom of each beam at the estimated location of plastic hinge formation, which was 0.75 in. from the edge of the moment-connection flange plates. Tension in the ropes was measured throughout the Northridge ground-motion testing of Frame 2 using four, 10,000-lb-capacity, Transducer Techniques tension load cells (Figure 5.17). All load cells were purchased specifically for this test, and were not used prior to the testing of Frame 2. For that reason, the manufacturer's calibration for the load cells was verified without additional documentation, using the Satec universal-type testing machine in the Virginia Tech Structures Lab. Load cells were installed at the upper end of each rope. Strains and load cell measurements were monitored and

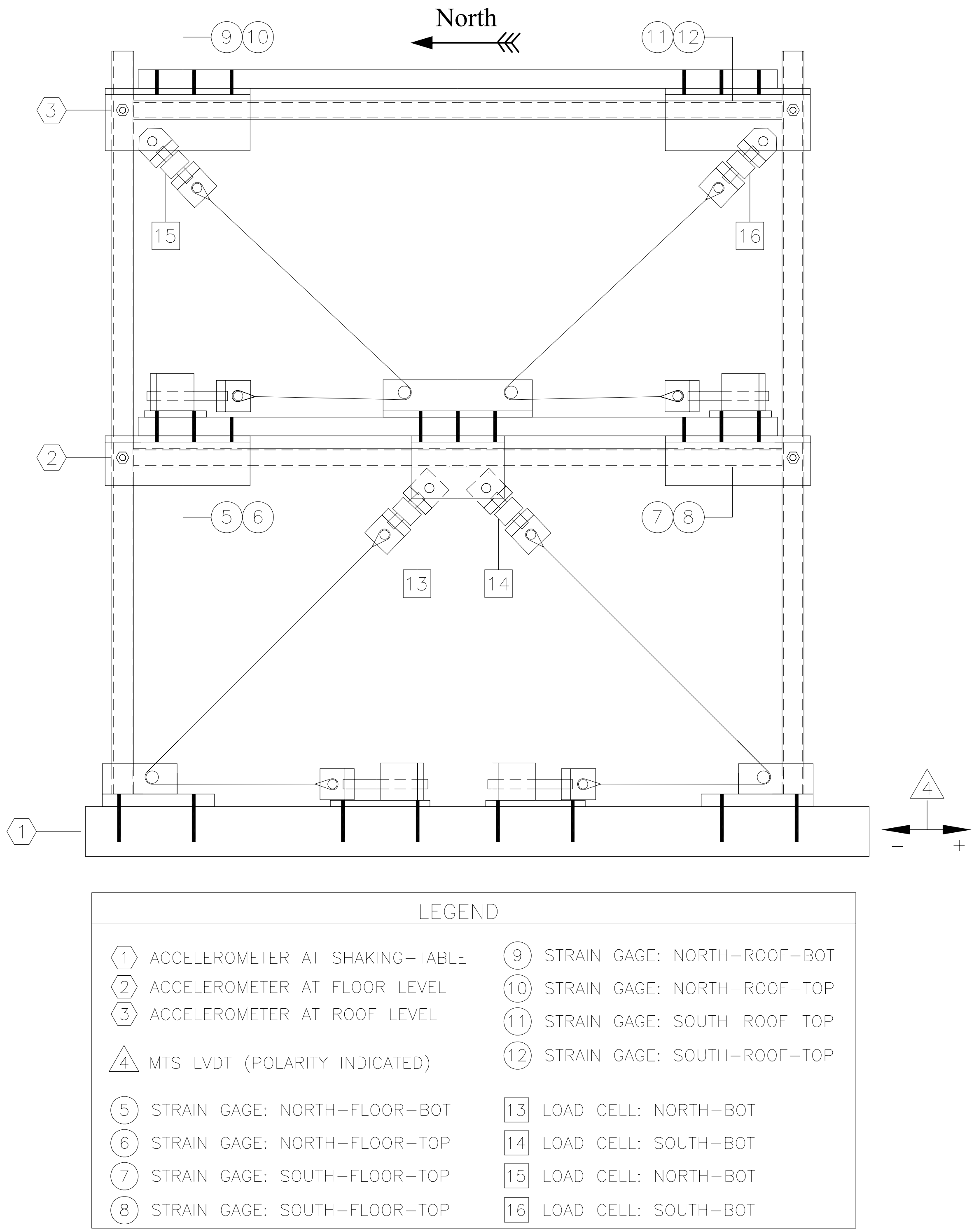


Figure 5. 16: Instrumentation Diagram for Northridge Shaking-Table Tests

recorded at a rate of 100 scans per second, or 0.01 second intervals, using a Cambell Scientific, Inc. high-speed data logger, model CR-9000 (CR-9000). It should be noted that the actuator position feedback signal was also recorded using the CR-9000, with the intent of being able to synchronize accelerometer data with strain and rope-force data. The position voltage signal was delivered to the CR-9000 through output channels on the front of the controller.

Figure 5. 17: Photograph of 10,000-lb Tension Load Cells

Residual deformation of the frame was determined after the 180% and 220% Northridge ground-motion tests by measuring the change in location of the floor and roof diaphragm levels with respect to the table location using a laser leveling device. This was done by marking a location on the table from a reference point at each diaphragm level before and after subjecting the frame to 180% and 220% ground motions, The distance between marks indicating residual drift was measured on the east and west sides at each diaphragm level. The average of east side and west side measurements was recorded as the residual drift for each level.

5.3.2 Northridge Ground Motion Input

Ground motion input for tests described in Chapter 5 was based on the ground motion recorded at the Sylmar County Hospital recording station near Los Angeles, California, during the Northridge Earthquake of 1994 (Figure 5.18). To cause deformation in the steel moment frame required for yielding in the beams, it was determined in Chapter 3 that the Northridge acceleration record would need to be scaled by 180%. For additional insight into modification of frame behavior with the addition of ropes, a 30% test and a 220% test were also conducted. It should be noted that the magnitude of accelerations were constant between the full-scale prototype and the 1:6-scale model, and the time scale was condensed, based on similitude principles presented in Appendix B.

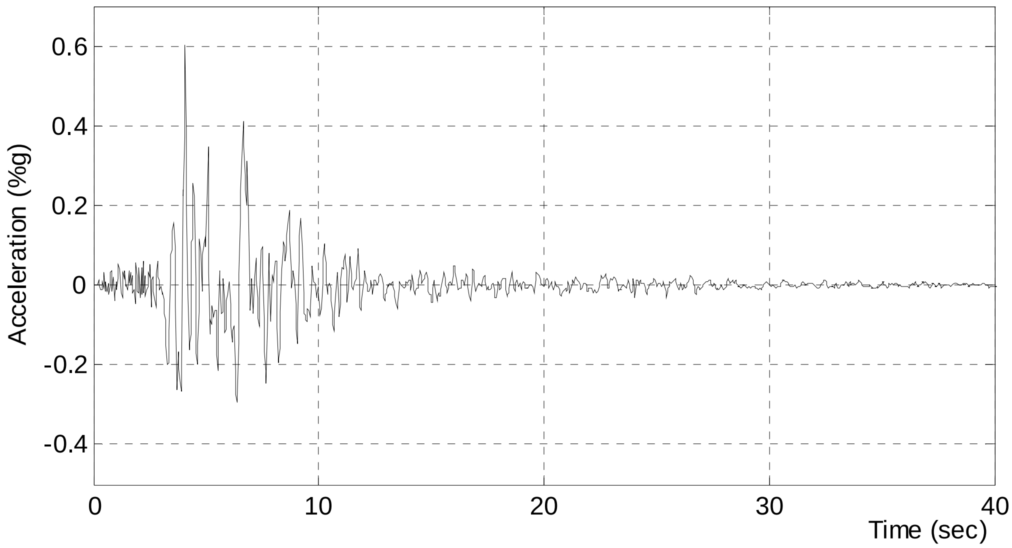


Figure 5. 18: Northridge Acceleration History

Since the motion of the table was controlled by controlling the position shaking-table actuator, a displacement trace based on the Northridge ground motion accelerogram was required. The displacement history related to the PEER Strong Ground Motion record designated NORTH/SYL090 was obtained from the PEER Strong Motion Database (www.peer.berkeley.edu/svbin/GeneralSearch) and used to create the command voltage signal used to drive the shaking-table actuator. The displacement record obtained consisted of a series of displacement values at a constant interval of 0.02 seconds. The series was factored to convert the full-scale displacements to voltages necessary to replicate the displacement history at a 1:6-scale, corresponding to the 100% full-scale accelerations, as follows:

$$DV_{SCALE} = \frac{DH_{FULL}}{\lambda_L} \text{ x } \frac{V_{LVDT}}{\Delta_{STROKE}} \tag{5-1}$$

where DV_{SCALE} was the 1:6-scale displacement voltage, DH_{FULL} was the 100% full scale displacement history in inches, λ_L was the length scaling factor equal to 5.78, V_{LVDT} was the absolute value of the voltage range of the LVDT internal to the shaking-table actuator in each direction (10 in.), and Δ_{STROKE} was the absolute value of the range of the shaking-table actuator in each direction (3 in.).

The resulting series could not be used as a command signal because it would be interpreted as a step function by the Schenck controller, resulting errantly in small impacts as the actuator transitioned instantaneously from one position to the next. To produce a smooth signal required to transition between voltage values, additional steps were required. First a program was written to create a series comprised of scaled displacement voltages, and the slope required to transition from one voltage value to the next based on the scaled time increment, as follows:

$$TS_{SCALE} = \frac{T_{FULL}}{\lambda_T} \tag{5-2}$$

$$b_{TCi} = \frac{V_{i+1} - V_i}{T_{SCALE}} \tag{5-3}$$

where T_{SCALE} was the 1:6-scale time increment (0.00823 sec), T_{FULL} was the full-scale time increment (0.02 sec), λ_T was the time scaling factor equal to 2.4, V_i was the i^{th} voltage, and b_{TCi} was the slope of the transition curve between voltage values.

The result was a series of alternating voltage and transition curve slope values. A stand-alone MTS micro-profiler was used to interpret this series and generate a continuous external voltage command signal. Figure 5.19 illustrates the 100% full scale displacement history with respect to time, and Figure 5.20 illustrates the corresponding 100% 1:6-scale voltage command signal with respect to time.

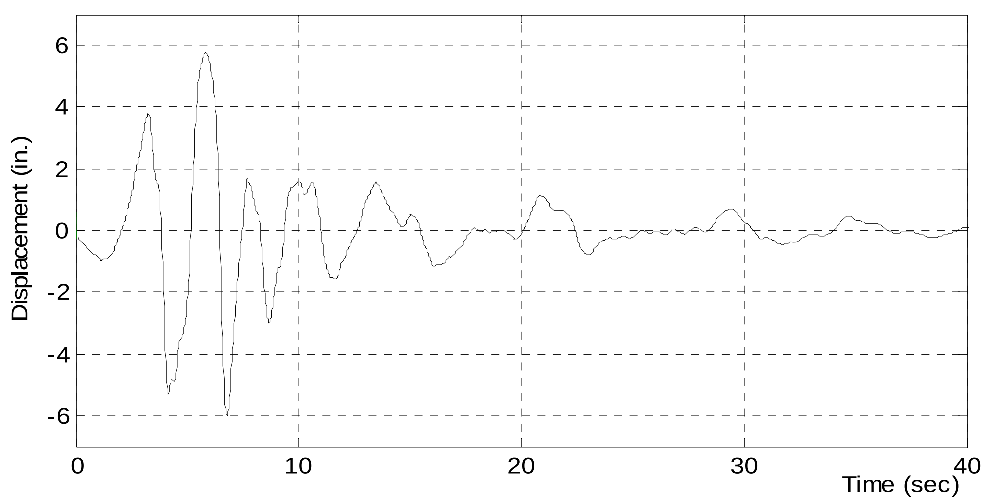


Figure 5. 19: 100% Full-Scale Northridge Displacement History

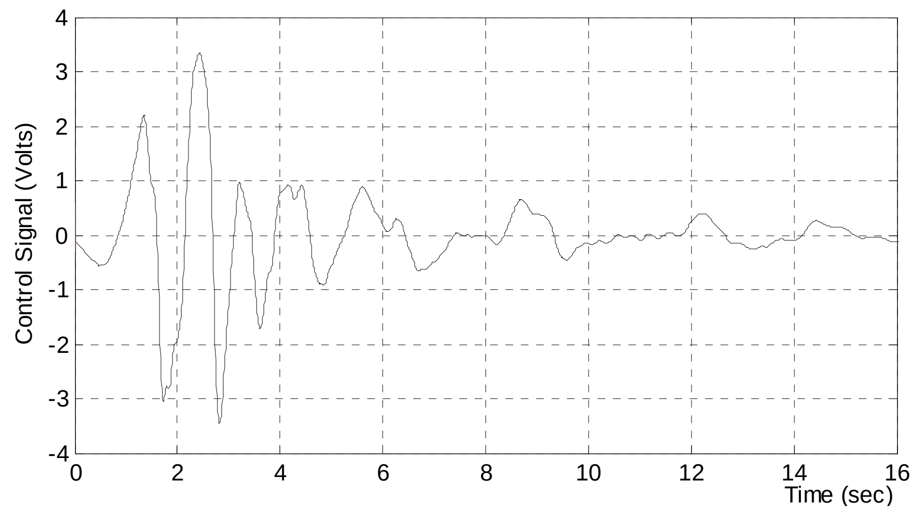


Figure 5. 20: 100% 1:6-ScaleVoltage Command Signal

To obtain actual command voltage signals used in the Northridge ground-motion tests, the 100% 1:6-scale voltage command signal was simply factored by 0.3, 1.8, and 2.2 to obtain 30%, 180%, and 220% Northridge ground motion records respectively (Figure 5.21).

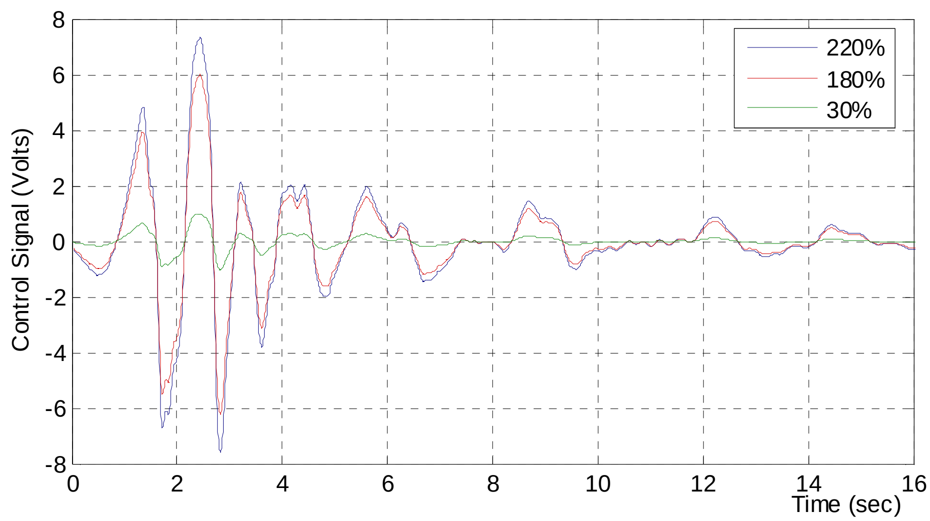
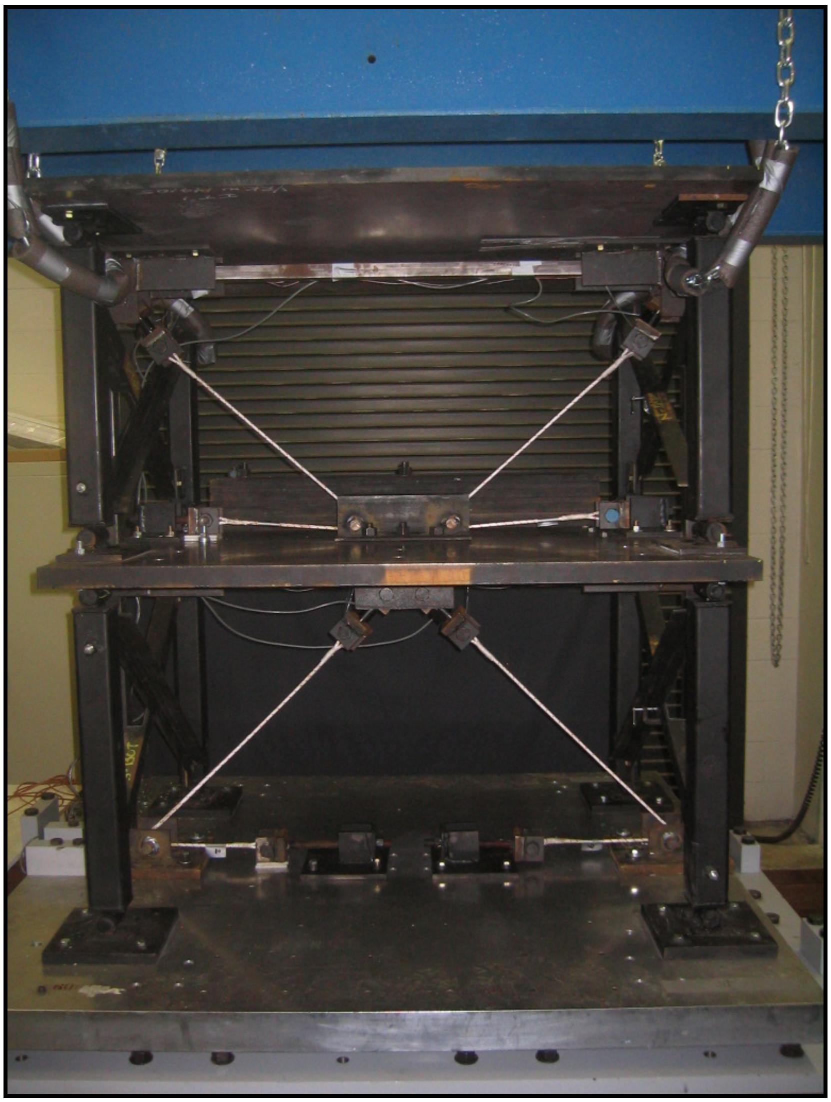


Figure 5. 21: Illustration of the 30% 180%, and 220% Voltage Command Signals

The method outlined above was previously used to simulate the Northridge ground motion in shaking-table ballast tests, documented in Appendix C. Excellent correlation was obtained between the simulated 1:6-scale ground motion acceleration and the full-scale ground motion acceleration histories in the time domain and frequency domain, reported in Appendix C.

5.3.3 ROPE CONNECTIONS

Figure 5.22 illustrates the configuration of the ropes for NR-2-series tests. In general the rope was connected at the high side to the load-cell. The length of the rope required for the test was longer than the available diagonal length between connection points and less than the length required for the load cell attachment. The rope was therefore passed through a 1-in. diameter fixed rod at the floor diaphragm, where it was turned parallel to the floor diaphragm, and connected to a fixture, used for adjustment of the initial rope condition.



Note: Near side ballast stack removed for clarity

Figure 5. 22: Photograph of Frame 2 with Ropes Installed

A combination of pinned gusset plate connections, threaded fixtures, and brackets was designed and fabricated for the purpose of connecting the rope to the frame. Two fixtures, consisting of a 0.75-in. plate with a tapped hole to match the threads of the load cell, with two 0.5-in.-thick gusset plates, were designed and fabricated for each load cell (Figure 5.23). In general, the fixture on one end was attached via a zero-tolerance pin to gusset plates, which were bolted with fully-tensioned bolts to the diaphragm levels (Figures 5.24 and 5.25). All bolt tensioning was done using the turn-of-the-nut method. The fixture on the opposite end of the load cell was attached to the rope via a zero-tolerance pin connection. The rope was then passed through a fixed rod, and welded between two gusset plates at the low end (Figures 5.26 and 5.27). The rope terminated at a fixture similar to the load cell fixtures. The fixture at the low end was attached to a threaded rod, which terminated in a three-plate fixture that was bolted to the floor diaphragm level or to the shaking table (Figures 5.28 and 5.29). The threaded rod was used to adjust the rope tension, such that the initial gap in the rope was approximately 0.2 in., corresponding to the response illustrated in Figure 5.1. The initial rope configuration was achieved experimentally by applying a 75 lb tension load to the rope using the nut attached to the UNC-16 threaded rod. The nut was then reversed three full turns. The adjustment nut is indicated in Figure 5.29.

Figure 5. 23: Photographs of Load-Cell Fixtures Attached to the Load Cell

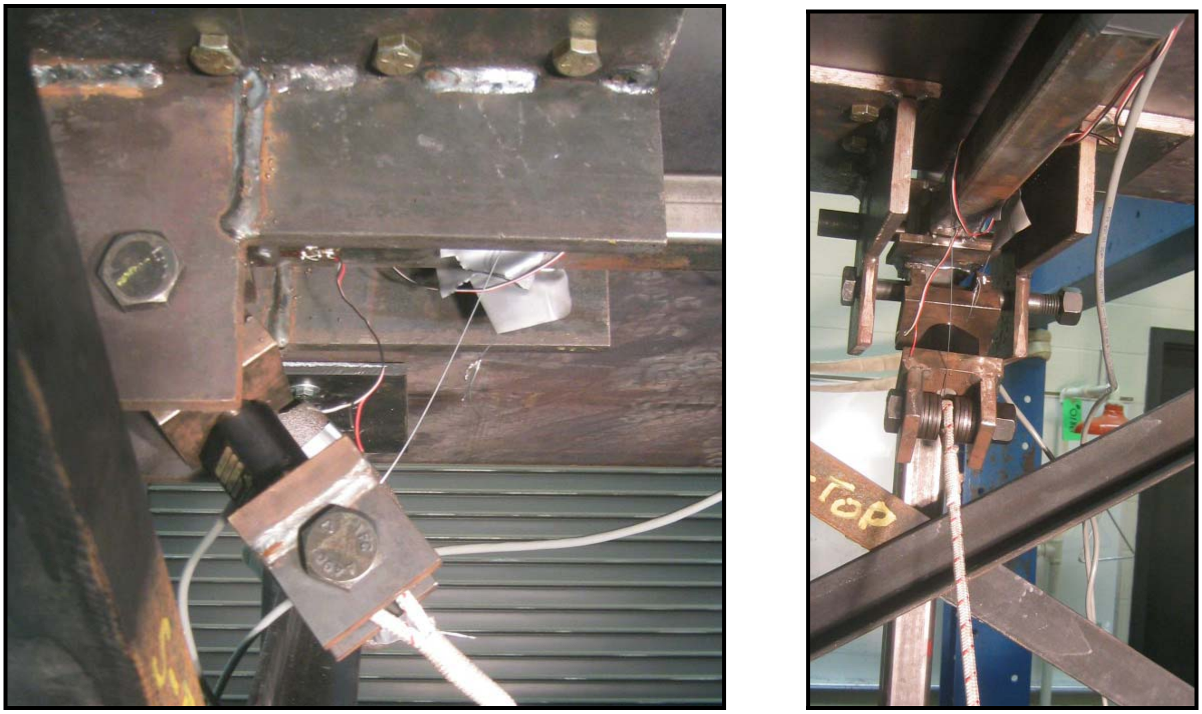


Figure 5. 24: Photograph of Load Cell Attachment at the Roof Diaphragm

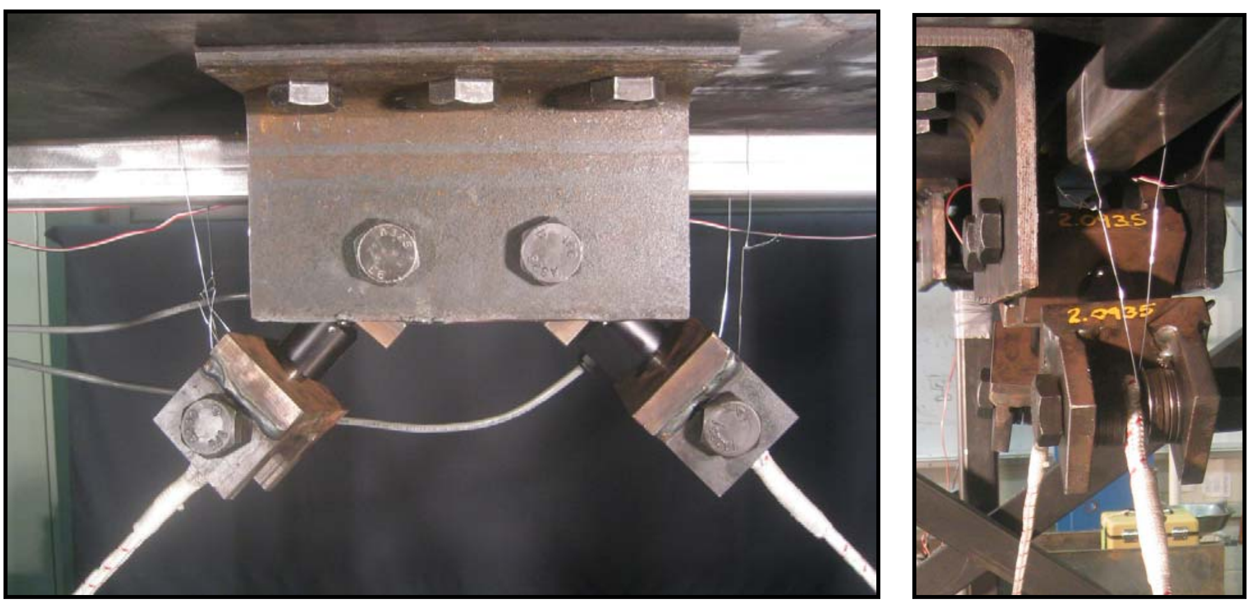


Figure 5. 25: Photographs of Load-Cell Attachment at the Floor Diaphragm

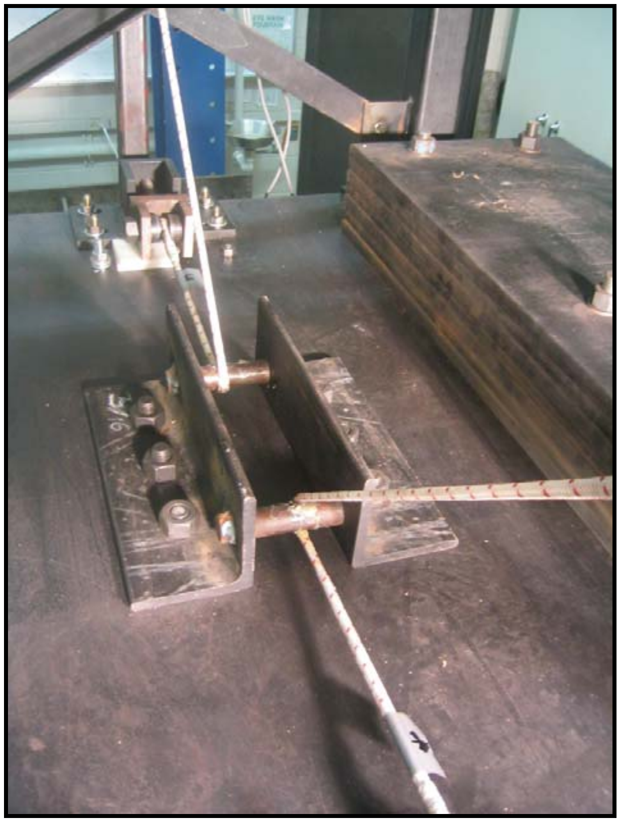


Figure 5. 26: Photograph of Rope Support at the Floor Diaphragm

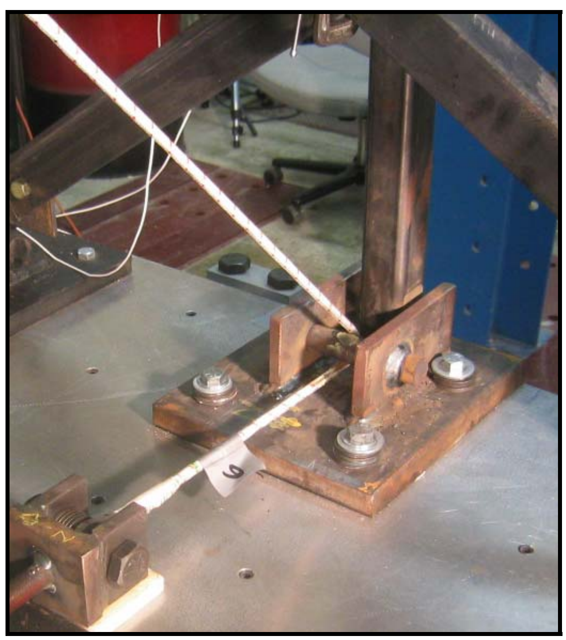


Figure 5. 27: Photograph of Rope Support at the Shaking Table Level

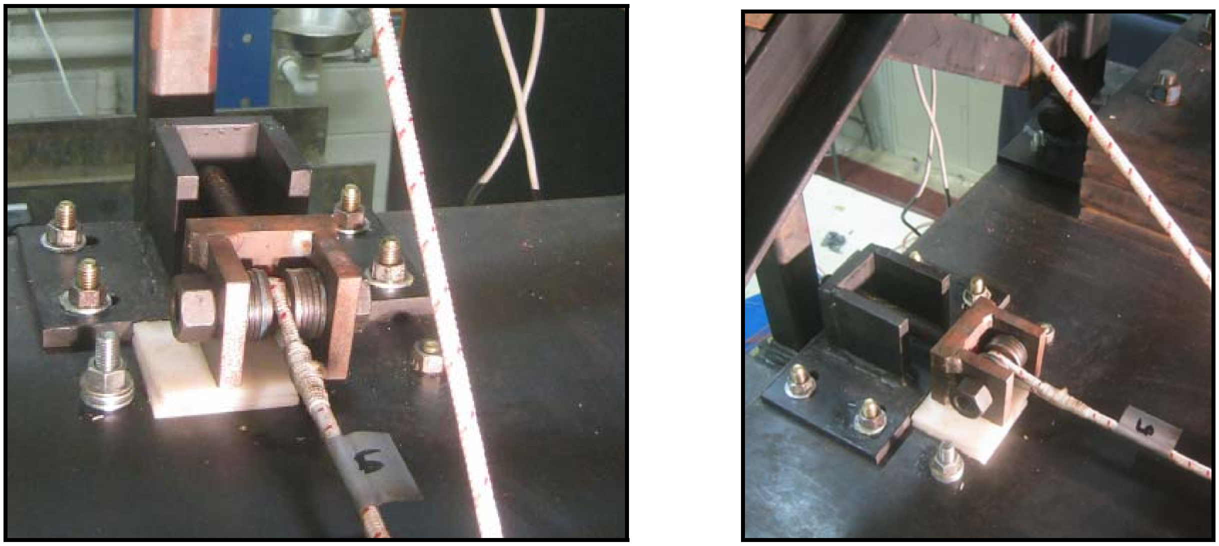


Figure 5. 28: Photographs of Adjustment Fixture at the Floor Diaphragm

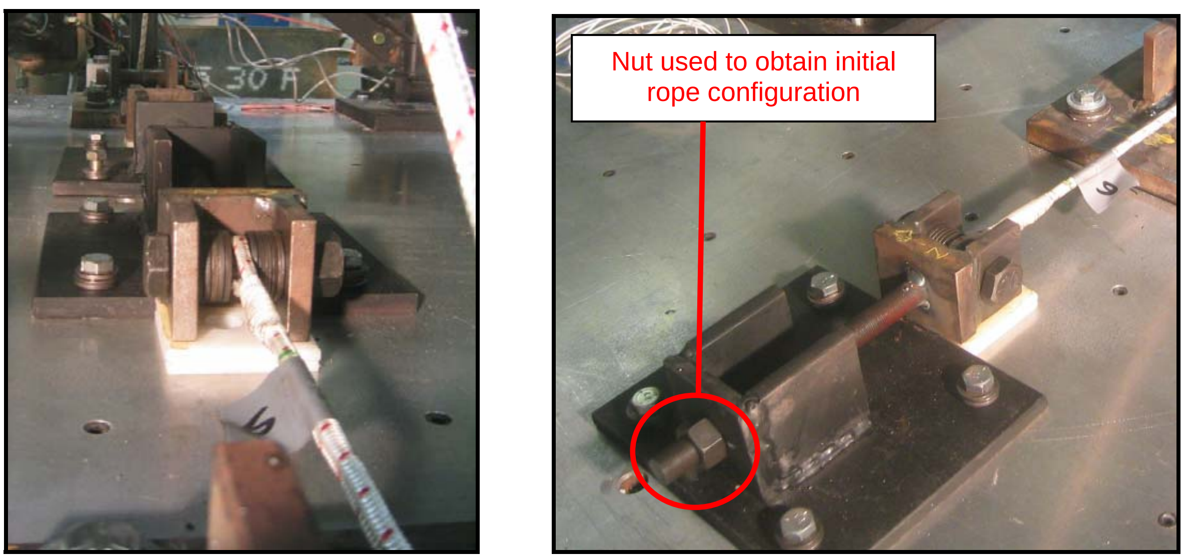


Figure 5. 29: Photographs of Adjustment Fixture at the Shaking Table

5.4 Experimental Results for NR-1-Series Tests (No Ropes)

This section reports the experimental results of Test NR-1-30 and Test NR-1-180 with corresponding results from the analytical DRAIN simulations of Section 5.2, and compares the experimental data with the analytical DRAIN results. These results include relative floor and roof displacement, roof and floor acceleration, total base shear, and residual drift. All results are reported for 0 to 15 seconds of ground-motion input, as all significant frame response of interest to this study occurred within 15 seconds of the initiation of the ground-motion input.

Relative experimental roof and floor displacements were determined using a Matlab (2005) subroutine shown in Appendix F. In general, the subroutine was written to filter an acceleration record and integrate the signal in the frequency domain to obtain a displacement trace. Specifically, the subroutine was written to perform a Fourier transformation on the roof and floor acceleration records, filter superfluous low and high frequencies of the resulting Fourier series, and integrate the resulting Fourier series twice. The Fourier series resulting from double integration represents displacement in the frequency domain. An inverse Fourier transformation is then performed on the Fourier series, resulting in a displacement trace in the time domain. This method results in reliable displacement traces for tests in which the frame remained elastic, Tests NR-1-30 and NR-2-30. However, this method was not reliable in determining an accurate displacement trace for tests in which inelastic deformation occurred, particularly after inelasticity of the frame was observed. This was due to the extremely low frequency required to represent residual deformation in the Fourier series.

Experimental roof and floor accelerations were determined for all tests by subtracting the recorded acceleration of the table from the recorded accelerations at the roof and floor diaphragm levels.

Experimental story-shear forces were determined by multiplying the floor acceleration by the roof ballast mass and multiplying the floor acceleration by the floor ballast mass. The total experimental base shear was determined by adding the story shears.

Residual drift measurements were made using a laser-leveling device, described in Section 5.3.1, and is reported for Test NR-1-180 and Test NR-2-180 in Section 5.4.2.

5.4.1 RESULTS OF TEST NR-1-30

Relative experimental roof and floor displacements for Test NR-1-30 are shown in Figure 5.30. The DRAIN simulation results were similar to the experimental results in shape as well as maximum and minimum values. The maximum and minimum roof displacements were overestimated in DRAIN by approximately 10% and 12%, respectively. The maximum floor displacement was overestimated in DRAIN by approximately 2%, And the minimum floor displacement was underestimated by approximately 5%. The DRAIN model predicted a slightly slower decay in displacement after 3.5 seconds than decay determined for experimental drift.

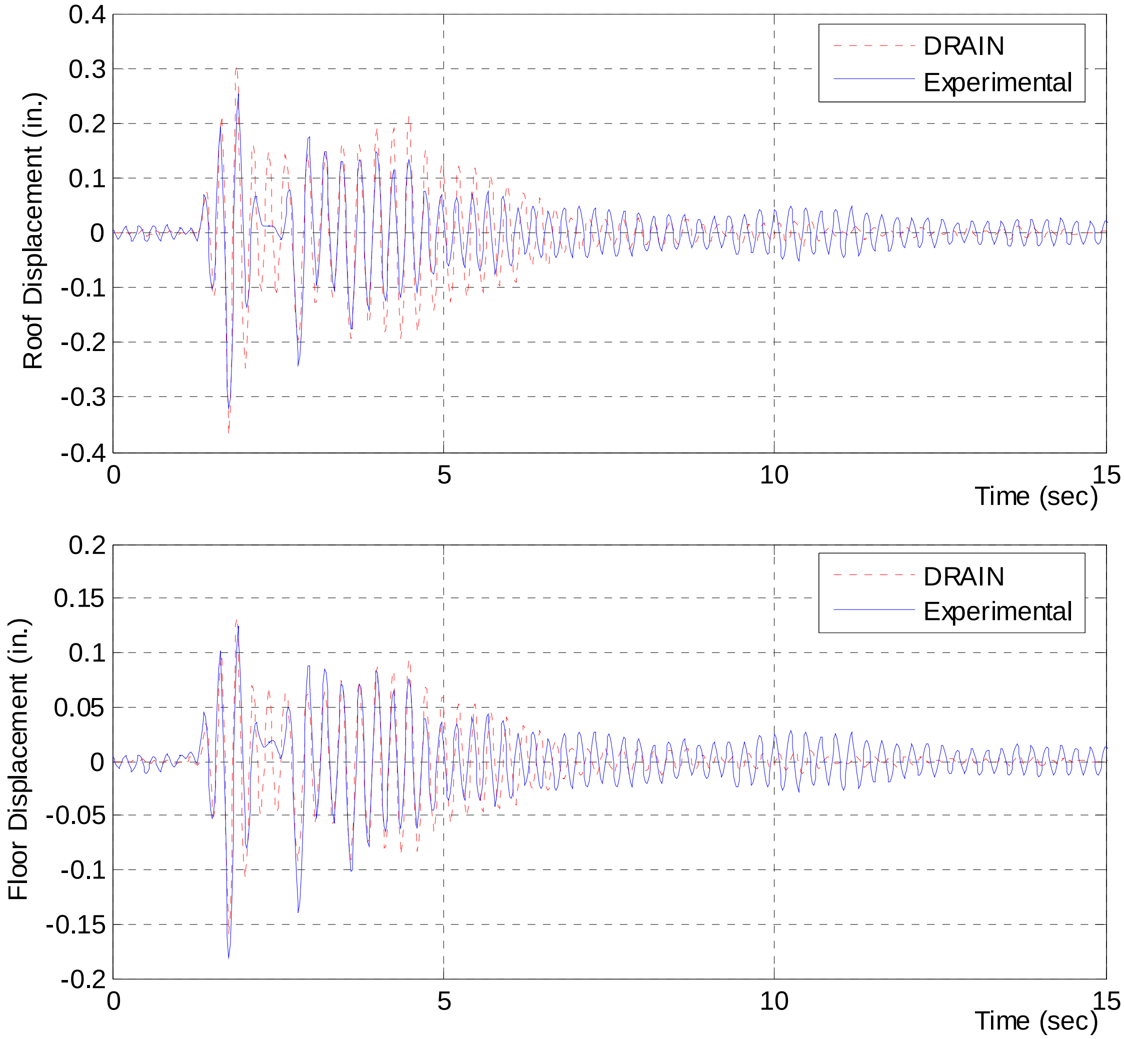


Figure 5. 30: Experimental Roof and Floor Displacements: NR-1-30

Experimental roof and floor acceleration traces for Test NR-1-30 are shown in Figure 5.31. In general the shapes of the predicted acceleration traces were very similar to the experimental shapes throughout the tests for the floor and the roof. The maximum roof acceleration was slightly overestimated in DRAIN by approximately 15%, while the difference in minimum values was more significant and appeared to be approximately 35%. The maximum and minimum floor acceleration values were much closer to those predicted in DRAIN.

Total base shear results for Test NR-1-30 are shown in Figure 5.32. The shape of the experimental trace matches the shape of the DRAIN model throughout the response history. The maximum and minimum values for base shear were nearly the same.

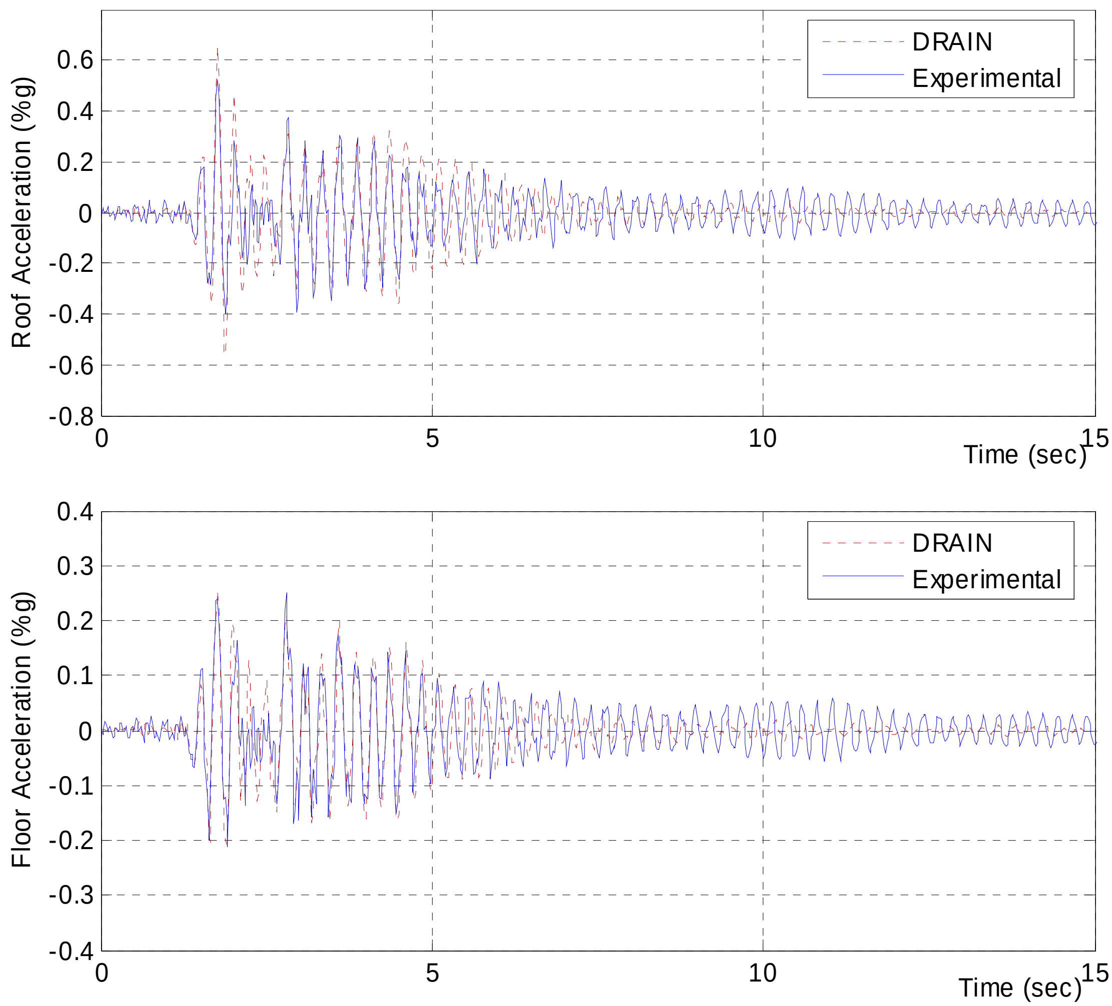


Figure 5. 31: Experimental Roof and Floor Acceleration: NR-1-30

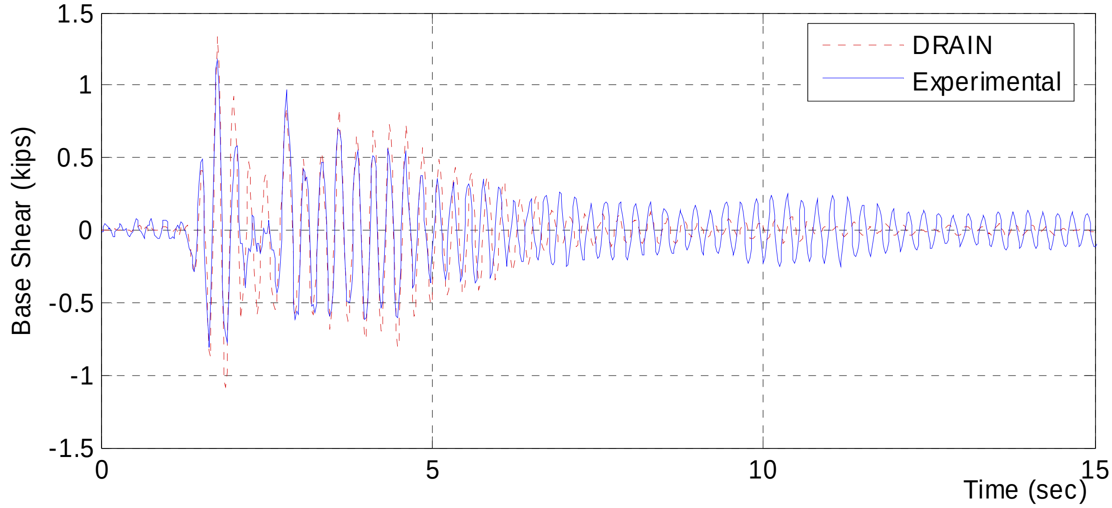


Figure 5. 32: Experimental Base Shear: NR-1-30

5.4.2 RESULTS OF TEST NR-1-180

Relative experimental roof and floor displacements for Test NR-1-180 are shown in Figure 5.33. It should be noted that the experimental displacement results for this test contain some error as a result of the limitations of the method used to determine displacement. The method was assumed to be accurate until the elastic limit of the frame was reached. For this test the elastic limit was surpassed at approximately 1.8 sec. The error related to this method was verified experimentally through the measurement of the residual drift (Table 5.2), which can be compared to absence of any residual drift calculated from experimental acceleration. Error in the calculated displacement trace was not quantifiable.

Experimental roof and floor acceleration traces for Test NR-1-180 are shown in Figure 5.34. In general the shapes of the predicted acceleration traces were very close from initiation of ground motion to approximately 3.5 seconds, with maximum and minimum values for roof acceleration being within 5% of predicted values, and maximum and minimum floor acceleration being within 30% of predicted values. After approximately 3.5 seconds the experimental acceleration trace decays rapidly with respect to the analytical decay trace. Total base shear results for Test NR-1-180 are shown in Figure 5.35. The shape of the experimental trace matches the shape of the DRAIN model through approximately 3.5 seconds of ground-motion input. Again the analytical predictions for maximum and minimum base shear were consistent with those recorded experimentally.

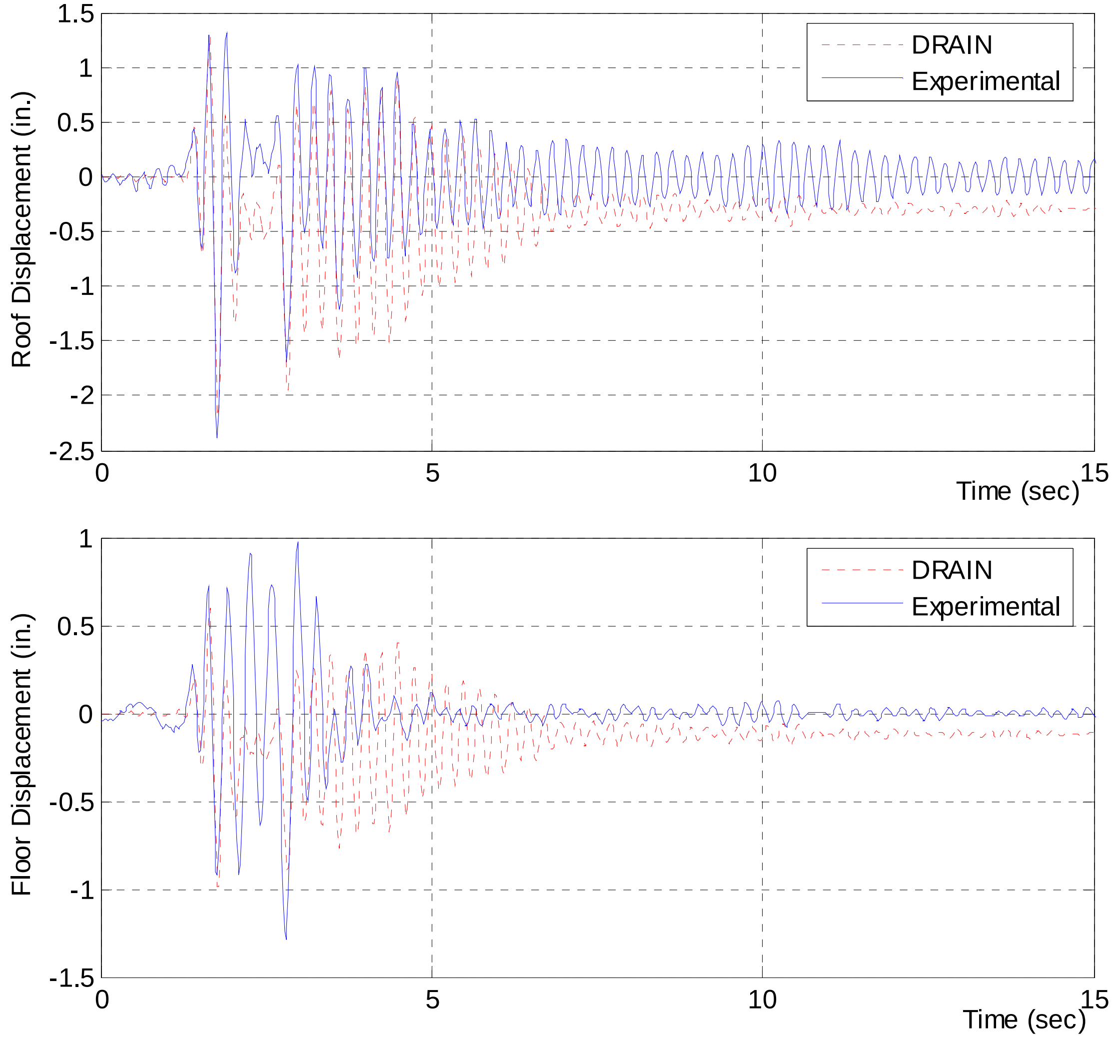


Figure 5. 33: Experimental Roof and Floor Displacements: NR-1-180

Residual drift measurements subsequent to Test NR-1-180 are reported in Table 5.2 with predicted values from the DRAIN analysis. After the test was completed, a noticeable lean in the frame was observed. A visual inspection of welds at all joints was done and all welds appeared to be intact with no fractures visible. Yielding at both ends of the first floor beams and at the column bases was evident by mill-scale flaking. No yielding was observed in the roof beams.

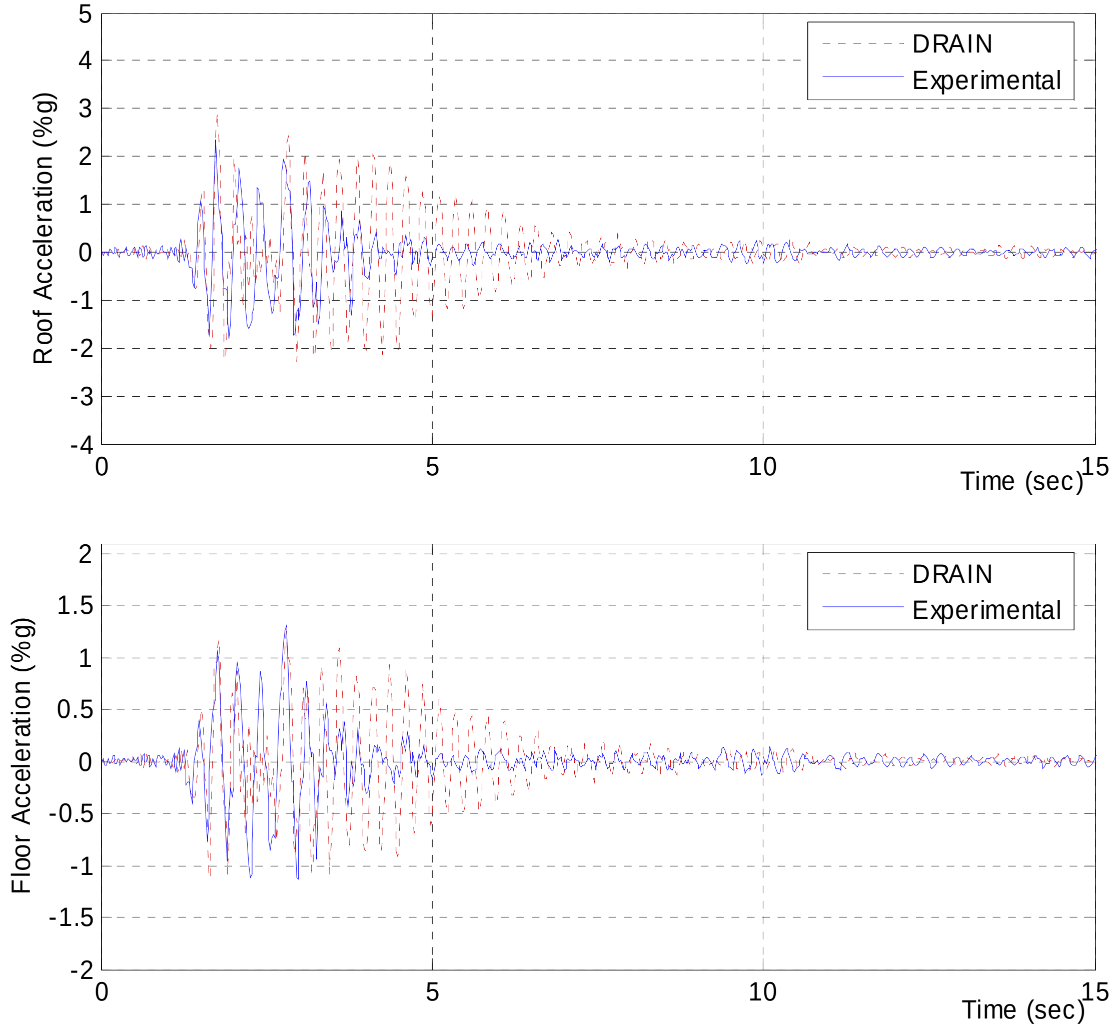


Figure 5. 34: Experimental Roof and Floor Accelerations: NR-1-180

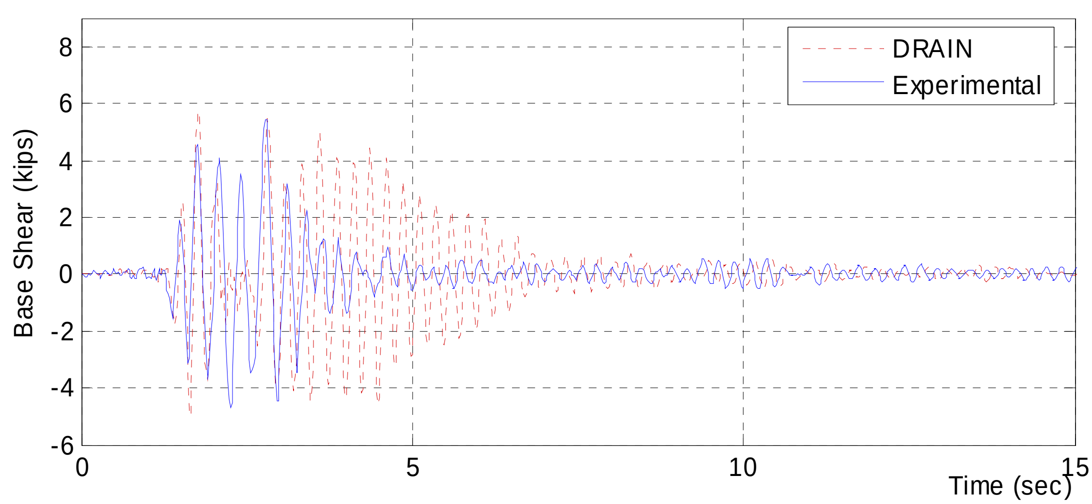


Figure 5. 35: Experimental Base Shear: NR-1-180

Table 5. 2: Residual Drift Measurements: NR-1-180

Diaphragm Level	East Side (in.)	West Side (in.)	Average (in.)	DRAIN (in.)
Floor	0.18	0.18	0.18	0.17
Roof	0.32	0.38	0.36	0.30

5.5 EXPERIMENTAL RESULTS FOR NR-2-SERIES TESTS (WITH ROPES)

This section reports the experimental results of Test NR-2-30 and Test NR-2-180 with corresponding results from the analytical DRAIN simulations of Section 5.2, and compares the experimental data with the analytical DRAIN results. These results include relative floor and roof displacement, roof and floor acceleration, total base shear, and residual drift. All results are reported for 0 to 15 seconds, as all significant frame response of interest to this study occurred within 15 seconds of the initiation of the ground-motion input.

Experimental relative floor and roof displacement, roof and floor acceleration, total base shear, and residual drift were determined as described in Section 5.4. Rope forces were recorded directly using instrumentation described in Section 5.3.

5.5.1 1:6-SCALE FRAME MODEL ROPE CONDITIONING AND INITIAL CONFIGURATION

The capability of the ropes to produce a non-deteriorating stiffness throughout multiple loading cycles was predicated on rope conditioning. The concept of conditioning ropes was developed in Chapter 2 and consisted of pre-loading the ropes above the maximum level of tension expected to allow large permanent deformations consistent with initial loading of new ropes, to occur prior to installing the ropes in a structure. An appropriate level of preloading required to condition the ropes used for the NR-20 series test was determined to be 2,900 lb. This preload was based on preliminary DRAIN modeling of NR-2-220, in which the maximum tension in the rope was predicted to be less than 3,000 lb, and the minimum rope break strength, equal to 4,000 lb. The Satec universal testing machine in the Virginia Tech Structures Lab was used to condition the ropes. Load was measured using a 10,000-lb tension load cell, and elongation was measured using a wire-potentiometer. Two cycles from zero load to 3,200 lb were completed for each rope.

5.5.2 RESULTS OF TEST NR-2-30

Relative experimental roof and floor displacements for Test NR-2-30 are shown in Figure 5.36. The DRAIN simulation results were similar to the experimental results in shape as well as maximum and minimum values. The maximum roof displacement was overestimated in DRAIN by approximately 23%. The minimum predicted roof displacement and maximum and minimum floor displacements predicted in DRAIN differed from experimental displacements by less than 1% . The DRAIN model predicted a slightly slower decay of displacement after 3.5 seconds than decay determined for experimental drift.

Experimental roof and floor acceleration traces for Test NR-2-30 are shown in Figure 5.37. The experimental and analytical response was very similar to those observed for Test NR-1-30. Because the rope elements were designed to have little effect on the overall system response at low-level excitation, this was expected. Comparisons regarding the shape of the floor and roof acceleration traces and the maximum and minimum values of floor and roof acceleration were similar to those of Test NR-1-30.

Total base shear results for Test NR-1-180 are shown in Figure 5.38. Again, the addition of ropes had little effect on the overall response of the system, and the maximum and minimum values predicted analytically were very close to those observed experimentally.

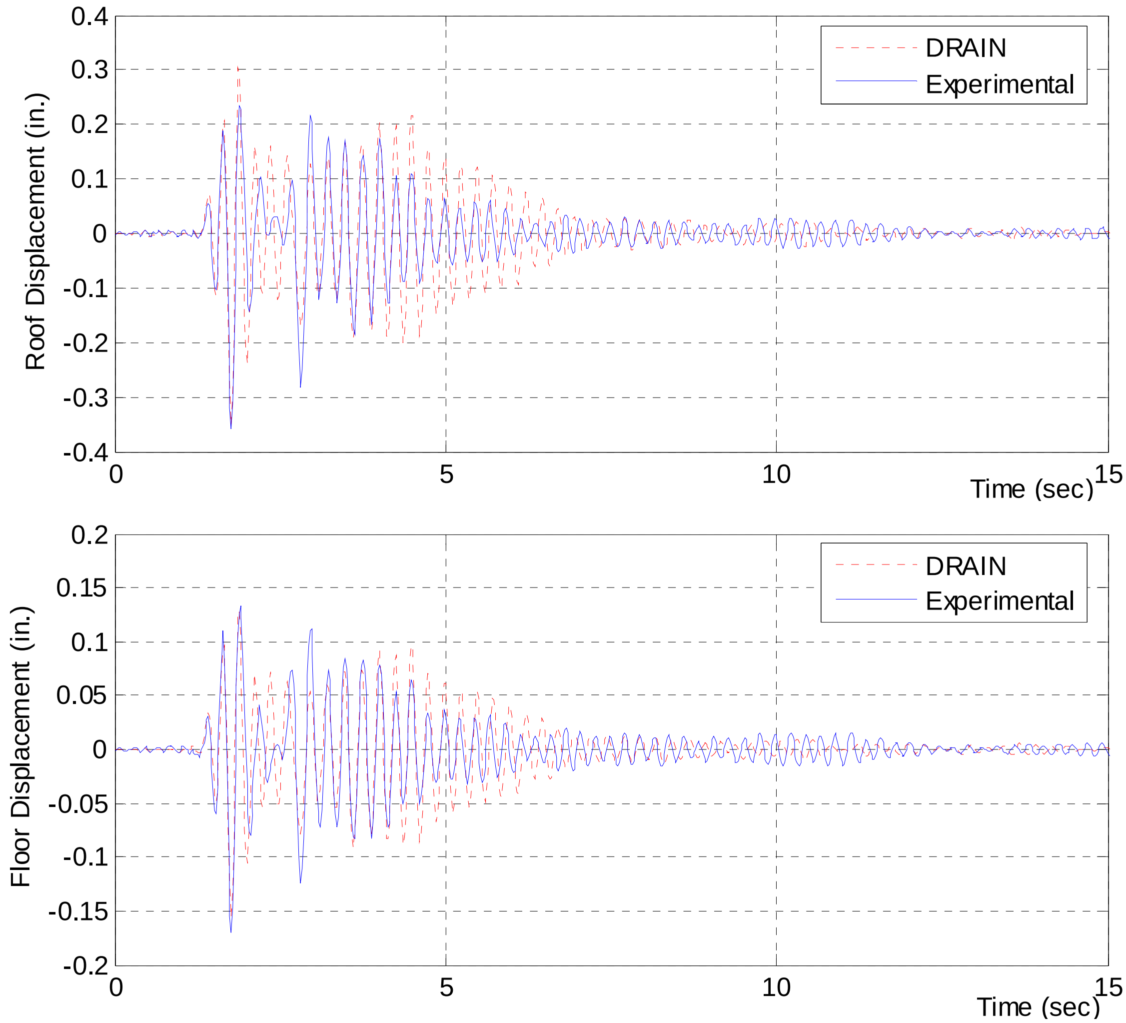


Figure 5. 36: Experimental Roof and Floor Displacements: NR-2-30

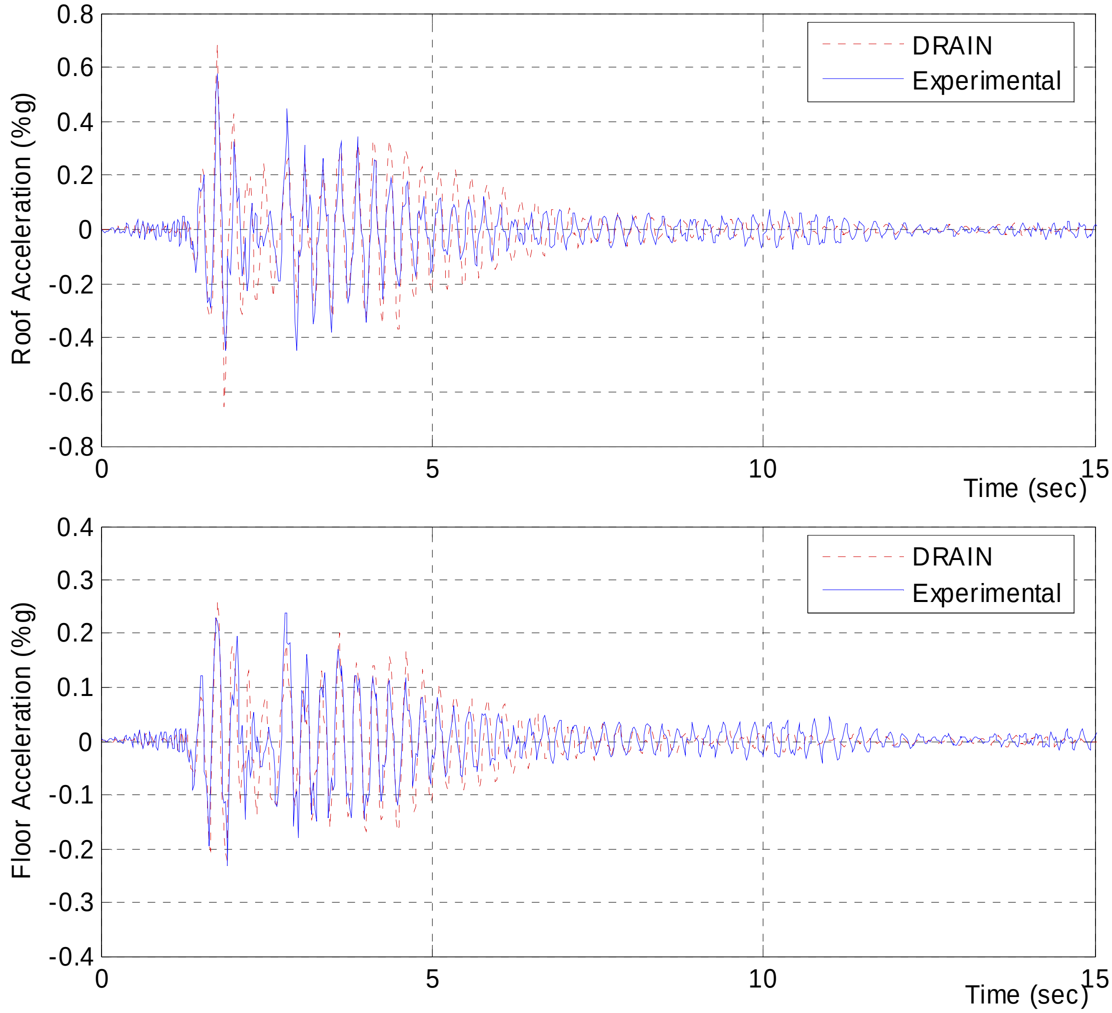


Figure 5. 37: Experimental Roof and Floor Acceleration: NR-2-30

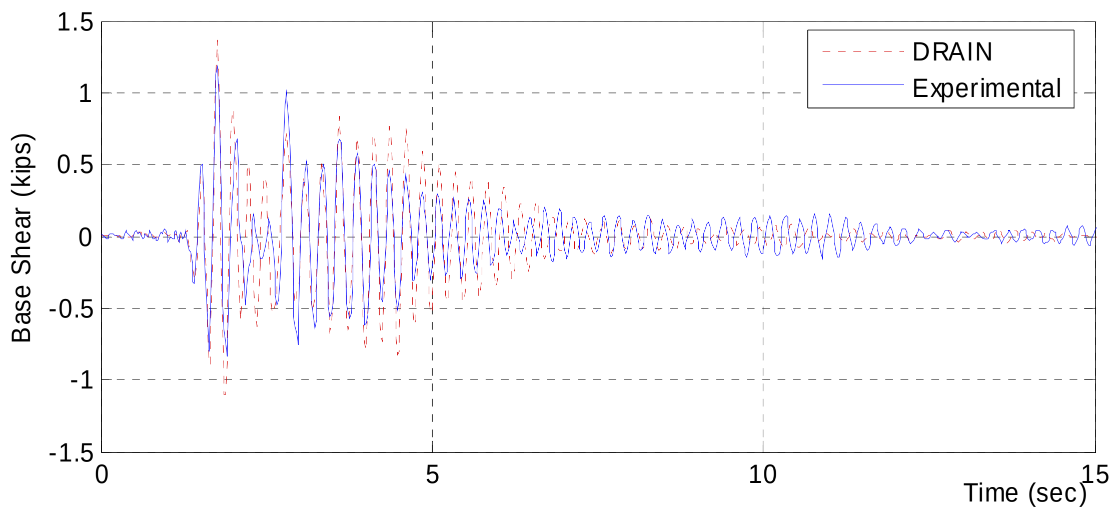


Figure 5. 38: Experimental Roof and Floor Acceleration: NR-2-30

Rope force traces with respect to time for each of four ropes used for Tests NR-2-30 are shown in Figures 5.39 through 5.40. The rope forces were very small with respect to the overall base shear. The maximum rope force value was 58 lb (Figure 5.39). The ropes were installed at a 45-degree angle within the frame. Therefore the resulting horizontal component of the maximum rope force was approximately 40 lb, which was approximately 0.3 percent of the maximum calculated base shear. This observation was consistent with the similarity observed between Test NR-1-30 and Test NR-2-30. Rope force traces observed experimentally take the general shape of those estimated in the DRAIN simulation. Ambient noise was observed in the load-cell signal and appears to be significant in the rope force traces in the range of force reported for Test NR-2-30. However, it should be noted that the noise represents less than ±10 lb, which was determined to be insignificant with respect to total base shear.

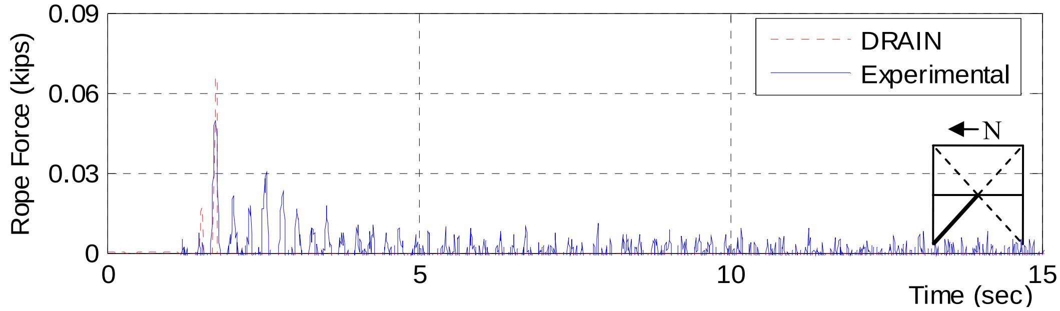


Figure 5. 39: Experimental Rope Force: Bottom North

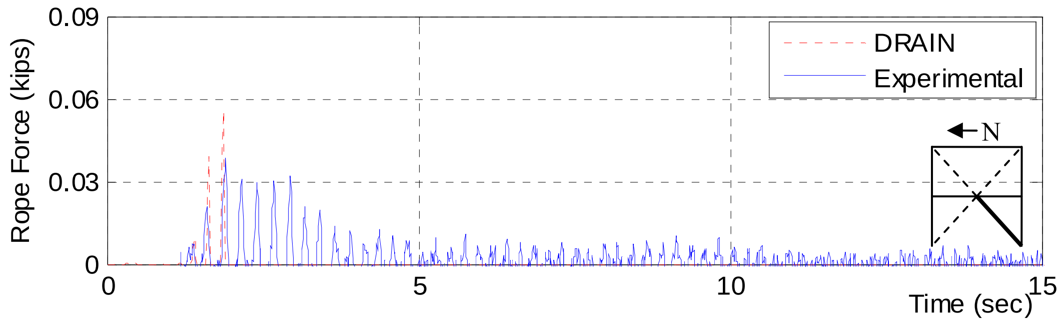


Figure 5. 40: Experimental Rope Force: Bottom South

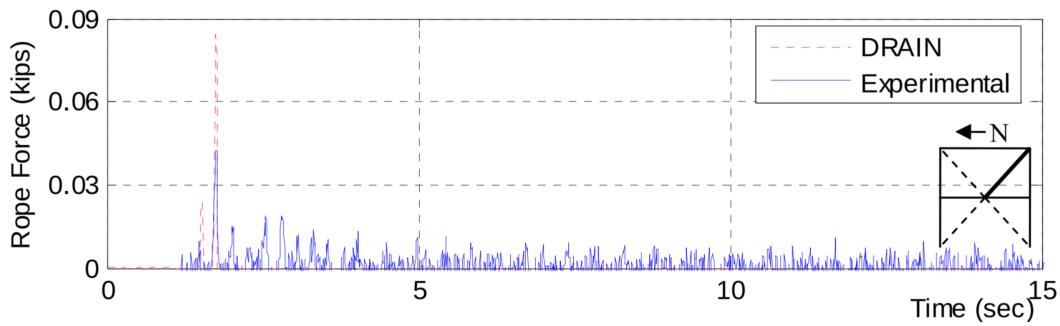


Figure 5. 41: Experimental Rope Force: Top South

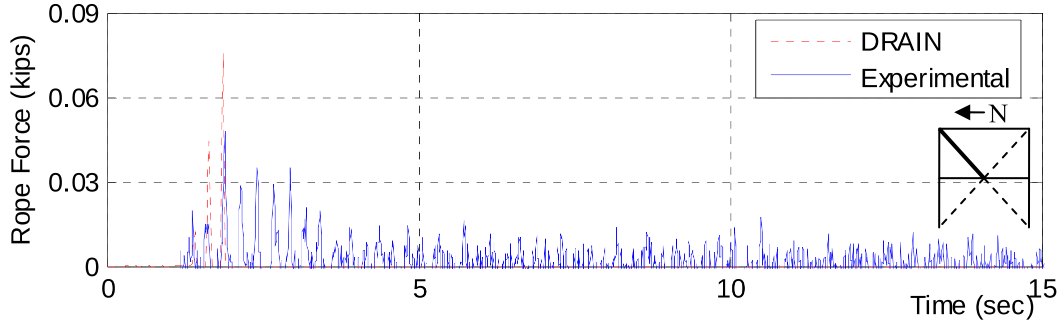


Figure 5. 42: Experimental Rope Force: Top North

5.5.3 RESULTS OF TEST NR-2-180

Relative experimental roof and floor displacements for Test NR-2-180 are shown in Figure 5.43. As was noted in the results of Test NR-1-180, the experimental displacement results for this test contain some error as a result of the limitations of the method used to determine displacement. Displacement traces calculated for Test NR-2-180 appear to contain relatively less error than those of Test NR-1-180 based on the relative shape of the displacement trace when compared to strain data, reported in Section 5.7. This was determined to be a reasonable conclusion due to the fact that the error in the calculated displacement trace was due to plastic deformation in the frame, which was observed to be less severe in Test NR-2-180 compared to Test NR-1-180. Error in the displacement trace was still evident based on residual drift measurements that were not present in the calculated displacement trace. Again, the error was not explicitly quantifiable.

Experimental roof and floor acceleration traces for Test NR-2-180 are shown in Figure 5.44. The maximum and minimum values for acceleration were overestimated by approximately 30%, while the general shapes of the traces were similar.

Total base shear results for Test NR-1-180 are shown in Figure 5.45. The total base shear traces were similar between the DRAIN model and the experimental results, with the exception of two positive peak values, which were over-estimated in DRAIN. The maximum base shear value calculated in DRAIN was approximately 20% greater than the corresponding experimental peak. The minimum base shear value calculated in DRAIN was approximately 20% greater than the corresponding experimental peak.

Rope force traces with respect to time for each of the four ropes used for Tests NR-2-180 are shown in Figures 5.47 through 5.50. It is evident that the rope forces were significantly overestimated in the DRAIN simulation throughout the loading history. Maximum rope force was observed in the North Bottom and South-Top ropes. The maximum predicted rope force values were 2.2 kips for each rope and were approximately 46% greater than the maximum rope force measured experimentally (Figures 5.46 and 5.49).

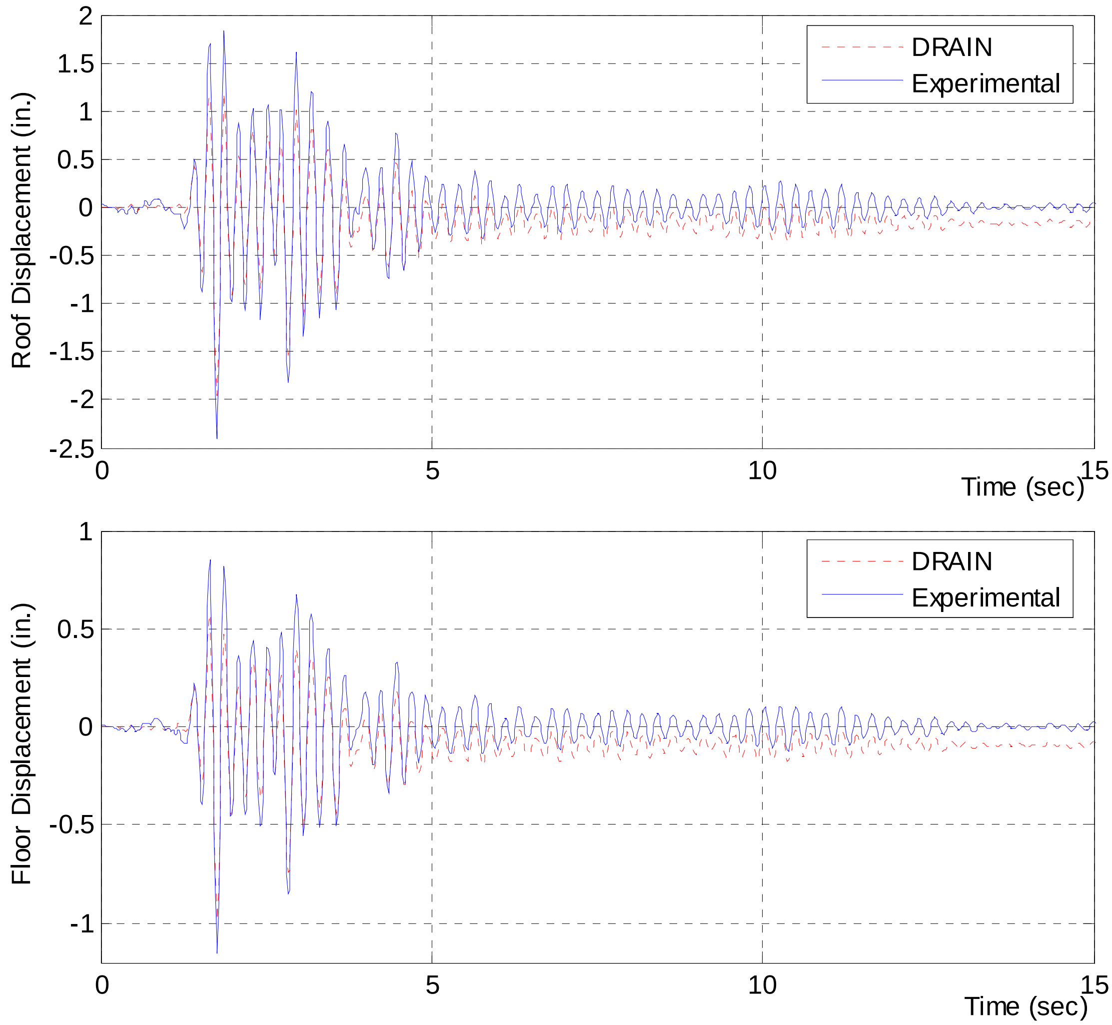


Figure 5. 43: Experimental Roof and Floor Displacements: NR-2-180

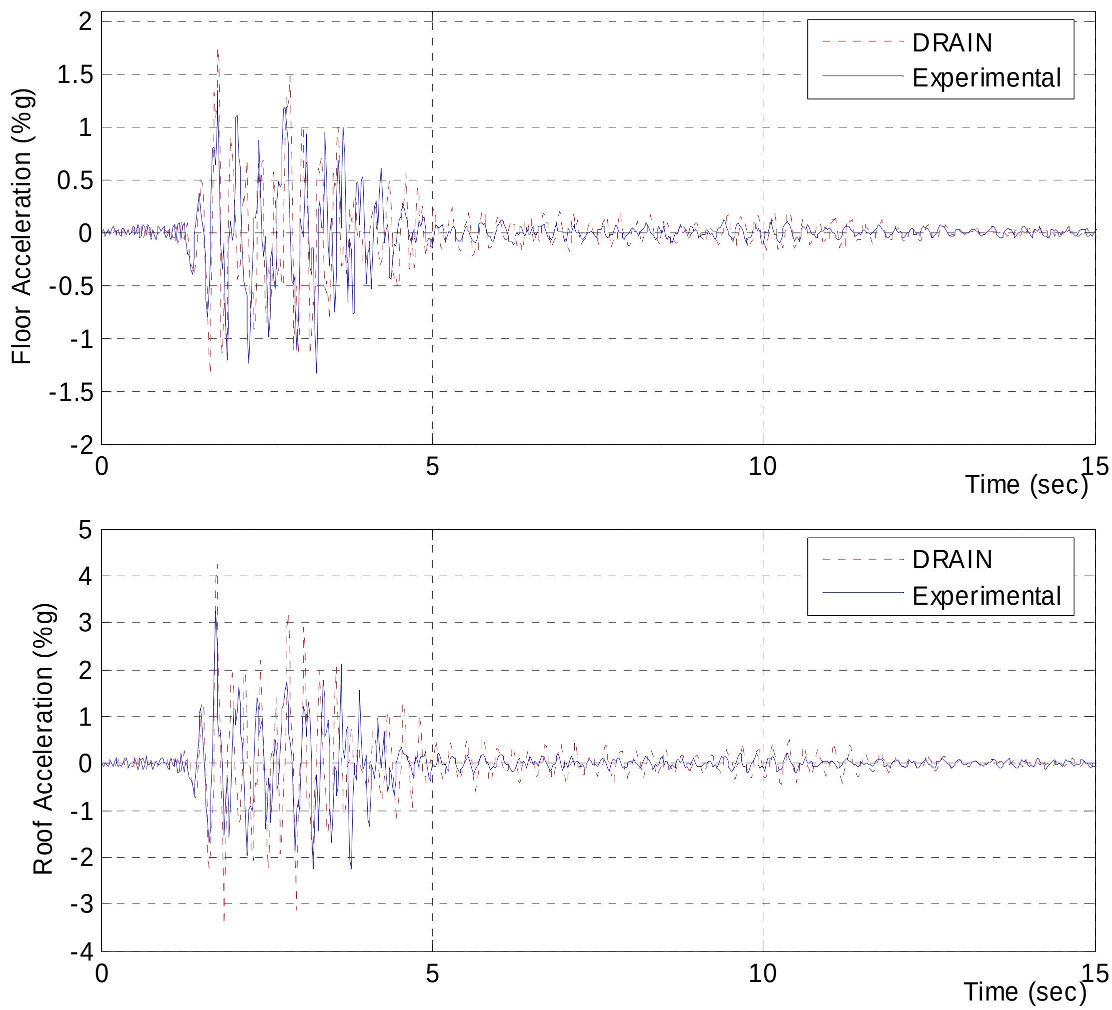


Figure 5. 44: Experimental Roof and Floor Acceleration: NR-2-180

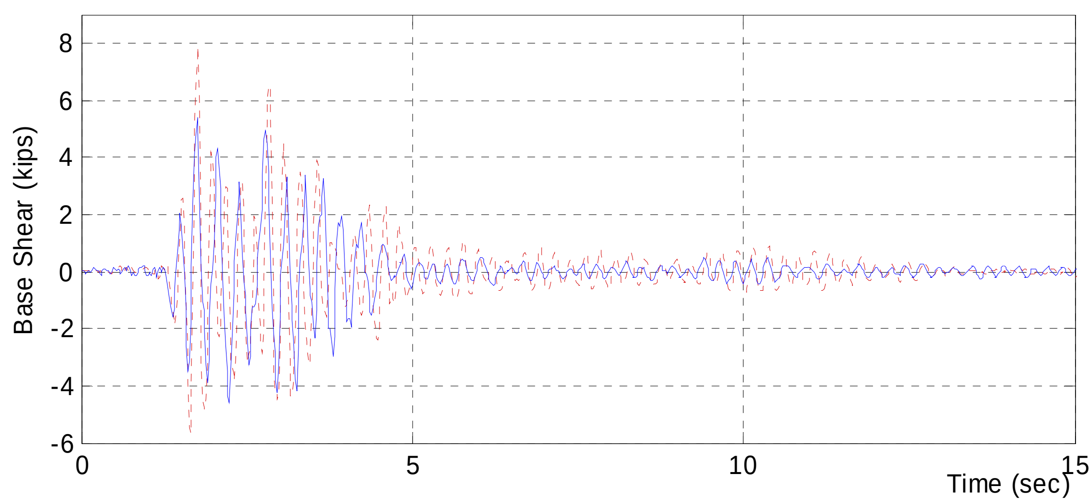


Figure 5. 45: Experimental Base Shear: NR-2-180

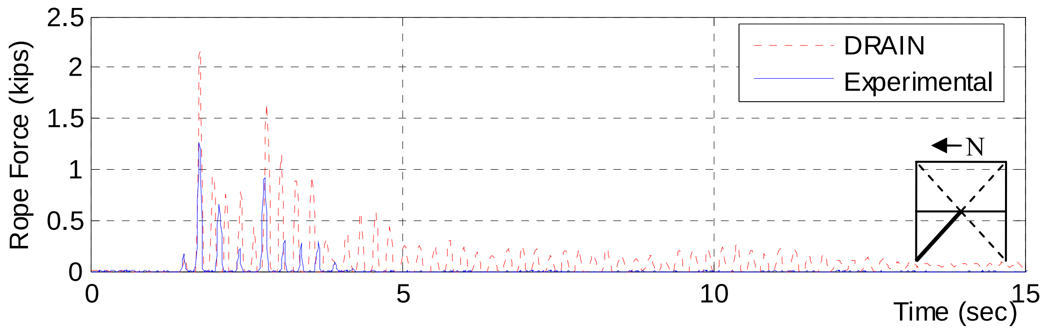


Figure 5. 46: Experimental Rope Force: North Bottom

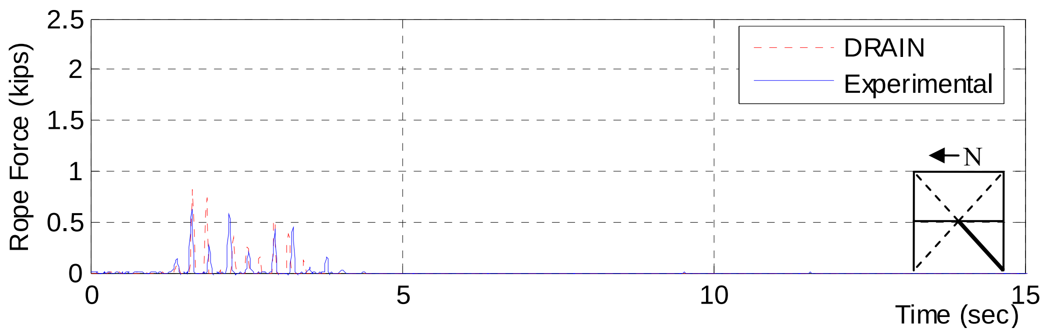


Figure 5. 47: Experimental Rope Force: South Bottom

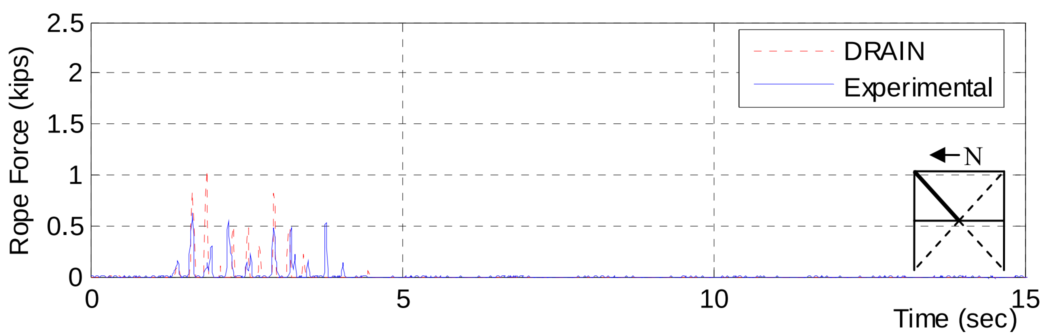


Figure 5. 48: Experimental Rope Force: North Top

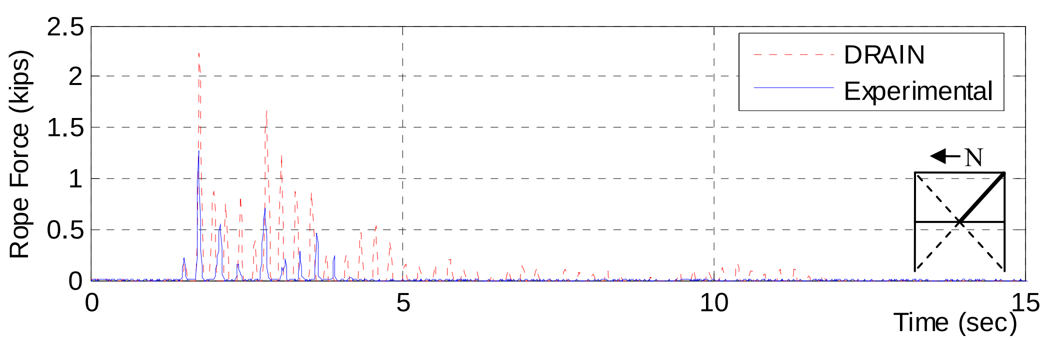


Figure 5. 49: Experimental Rope Force: South Top

Residual drift measurements made after Test NR-2-180 are reported in Table 5.3 with predicted values from DRAIN analysis. A visual inspection of welds at all joints was conducted and all welds appeared to be intact with no fractures visible. Yielding at both ends of the first floor beams and at the column bases was evident by mill-scale flaking. No yielding was observed in the roof beams, or in the columns at the diaphragm levels.

Table 5. 3: Residual Drift Measurements: NR-2-180

Diaphragm Level	East Side (in.)	West Side (in.)	Average (in.)	DRAIN (in.)
Floor	0.06	0.06	0.06	0.08
Roof	0.12	0.12	0.12	0.15

5.6 Evaluation of Analytical Model

Overall, the DRAIN model developed to predict 1:6-shaking table experimental results was adequate for the purpose of determining appropriate scaled Northridge ground motions to test the viability of the rope devices. It was important to predict levels of ground-motion input that would result in two distinct performance levels for Frame 1: a fully serviceable performance whereby resulting drift would be commensurate with service level wind drift, and collapse prevention performance, where inelastic deformation was evident subsequent to the event.

As reported above, a 60% Northridge ground-motion input was predicted to be the threshold of an elastic frame response. This was reduced to 30% for several reasons. The 30% level was predicted to result in a maximum elastic roof drift of 0.35 in., which was at the upper limit of commonly accepted drift allowed in practice. A common practical lower-bound limit for low and mid-rise structures, commonly taken as building height divided by story drift with consistent units, is 240. It should be noted that drift limitation for wind is not codified, and may vary based on design philosophy and specific building considerations. Further, a high level of confidence that the frame would remain elastic throughout Test NR-1-30 was established since predicted displacements induced with the 30% ground-motion were well below the elastic threshold of the frame. The experimental results relating to performance of the frame were as predicted in the DRAIN model. The frame remained elastic throughout loading for both 30% ground-motion tests. The maximum and minimum roof drift were determined to be within 12% of predicted values, and the maximum and minimum floor drift were determined to be within 5% of predicted values. Therefore, the DRAIN model was an excellent tool for predicting the performance level of the 1:6-scale model during the 30% ground-motion tests.

Predicting the response of the frame subjected to the 180% Northridge ground motion was the most crucial in this experiment. If only a small amount of yielding occurred during the test, it may have been difficult to evaluate improvement to the performance of the frame after adding ropes. If excessive yielding occurred, collapse was possible. Data from a test resulting in collapse would not have been useful, particularly if a test of the frame with ropes also resulted in collapse. It was therefore critical that a level of ground motion input was determined that would cause significant yielding in the frame, but would not induce a collapse. Results of sinusoidal input tests, reported in Chapter 4, compared to corresponding DRAIN predictions established confidence in the analytical model prior to testing. The confidence obtained was instrumental in establishing the 180% Northridge ground-motion as an appropriate input for producing the desired level of performance of the frame. The model predicted significant residual deformation in the frame when subjected to the Northridge ground motion and acceptable levels of base shear and maximum and minimum drift. A review of Test NR-1-180 test results reveals that residual drift was significant and that the base shear was adequately predicted. Due to the error involved in calculating displacement with respect to time, it was difficult to evaluate the accuracy of maximum and minimum floor and roof drift predicted by the DRAIN model. However, based on acceleration comparisons between the DRAIN model and experimental results, the maximum and minimum displacement values predicted by DRAIN appear reasonable. Therefore, the use of the DRAIN model in determining a performance level of the 1:6-scale model resulting from 180% Northridge ground-motion input was considered successful.

A more specific comparison of the DRAIN model results with respect to experimental results was also made for the purpose of evaluating the suitability of the model for predicting frame response with and without ropes. Aspects of frame response considered included accuracy of acceleration and displacement traces, total base shear traces, rope force, and residual drift. Strengths and deficiencies of the DRAIN model with respect to these aspects were considered.

Correlation was analyzed between accelerations, displacements, and base shear predicted by the DRAIN model and those observed experimentally for Tests NR-1-30 and NR-2-30. The capability of accurately predicting an elastic dynamic response of the frame was demonstrated in the comparisons of Sections 5.4.1 and 5.5.2. Some minor inconsistencies were observed in the acceleration traces with regard to peak values. The rate of decay of the response after the most intense portion of the ground motion was experienced, was slightly higher than predicted. This was attributed to non-linear damping of the model frame, which could not be modeled in DRAIN. Close correlation between displacement traces and base shear traces was observed. Overall, all aspects of experimental response were predicted with very good correlation, and the DRAIN model was evaluated as an excellent predictive tool for the elastic response of the frame.

Correlation of experimental results with the analytical simulations for Test NR-1-180 and Test NR-2-180, was somewhat less impressive. With respect to predicting accelerations, the DRAIN model consistently predicted higher maximum and minimum values, exceeding recorded values by as little as 5% and as much as 35%. As a result, the base shear predictions were somewhat higher than base shear observed experimentally, but to a lesser degree. The decay rate of the acceleration trace was largely underrepresented in the DRAIN model. This was attributed to higher damping present in the experimental system at higher levels of displacement, which was not modeled. When comparing analytical versus experimental displacement, the traces appear to be relatively similar, with maximum and minimum displacements being over-predicted by 10% to 20%. However, due to the non-quantifiable error involved in the calculation of experimental displacement, any evaluation of the correlation between analytical predictions and experimental results must be made with the understanding that experimental displacements were not true measured displacements. The DRAIN predictions for residual drift were very accurate for direction and magnitude. Rope force magnitudes were consistently overestimated by as much as 100% in the DRAIN model, but with good correlation between the analytical and experimental location of the peaks in time.

Overall, the DRAIN model was reasonably accurate in predicting the dynamic response of the frame with and without ropes. However, the inability to accurately model non-linear damping of the frame, post-yield response, and maximum rope force resulted in inaccuracies of analytical predictions throughout the loading history. Correlation between maximum and minimum values for acceleration, base shear, and residual drift was considered to be reasonably accurate.

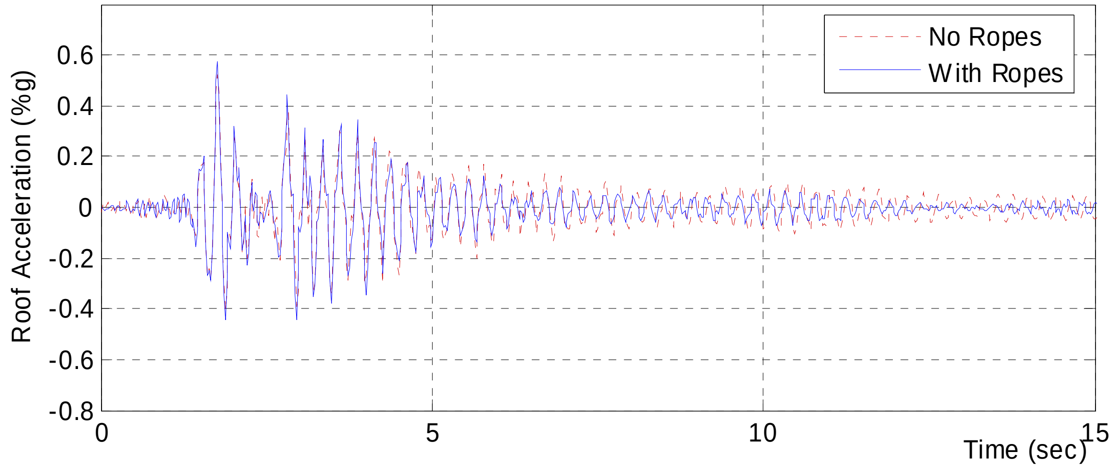
5.7 Comparison of Experimental Results of Frames with and without Ropes

This section compares the dynamic response and performance of the frames tested with and without rope devices installed. A brief comparison of Test NR-1-30 and Test NR-2-30 is presented. Performance comparison of the frame with and without rope devices installed is discussed based on residual drift and strain data for 180% and 220% Northridge ground-motion tests. Roof acceleration and base shear results provide the basis of dynamic response comparison for the 180% and 220% tests.

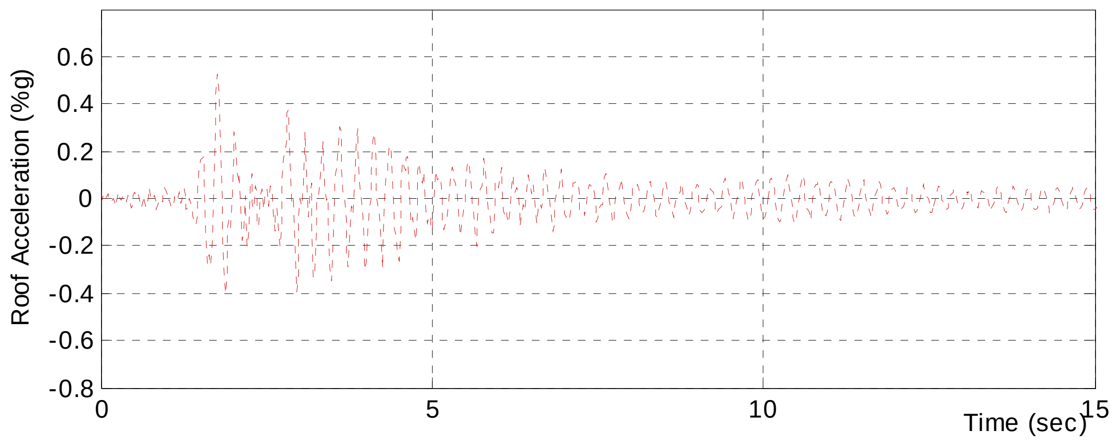
5.7.1 Tests NR-1-30 and NR-2-30

Roof displacement, roof acceleration, and base shear comparisons of Test NR-1-30 and NR-2-30 are shown in Figures 5.50, 5.51, and 5.52 respectively. As expected, the addition of the ropes had little effect on the low-level response experienced by the frame. The acceleration, displacement, and base shear traces for Test NR-1-30 were nearly identical to those of NR-2-30, indicating that the ropes contributed very little to the response. This was considered to be an important aspect of the rope devices. In previous tests the ropes were shown to have some permanent deformation after experiencing significant load. Under normal service conditions, such permanent elongations could inhibit the performance of the rope devices, which were designed to be effective in a large seismic event.

In Test NR-2-30, the ropes experienced a maximum force of 58 lb corresponding to 2% of the 3,000 lb rope conditioning force. The condition of the ropes was checked after Test NR-2-30 and it was verified that permanent elongation had not occurred. The maximum frame drift at the roof was determined to be 0.31 in., corresponding to a total height to drift ratio of approximately 180, or 0.6% of the total frame height. Therefore, when the frame experienced elastic drift, which was greater than drift commonly allowed due to service wind loads or relatively small seismic events, rope forces were not sufficient to induce permanent deformation in the rope devices.

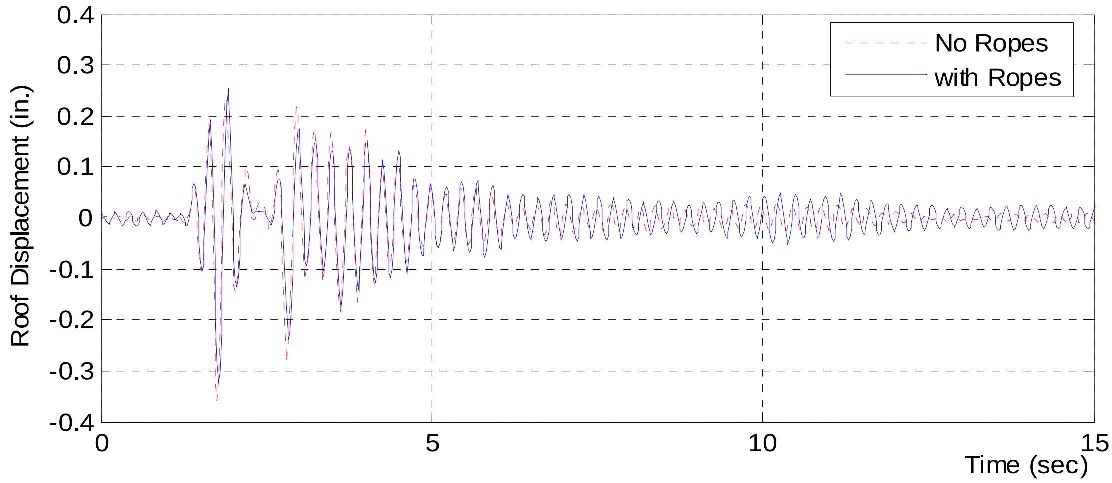


a) Comparison of NR-1-30 and NR-2-30

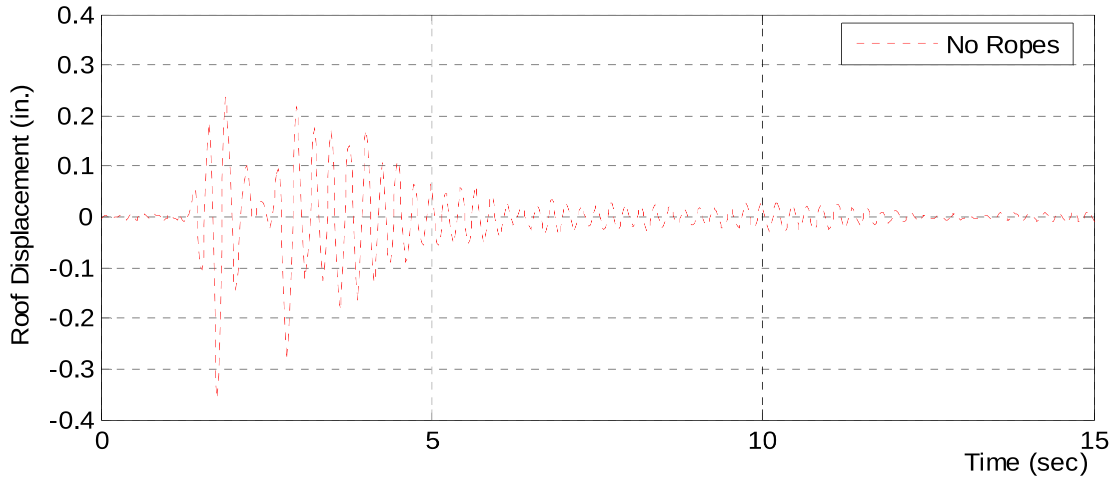


b) NR-1-30 Results Shown Separately for Clarity

Figure 5. 50: Roof Acceleration Comparison: NR-1-30 and NR-2-30

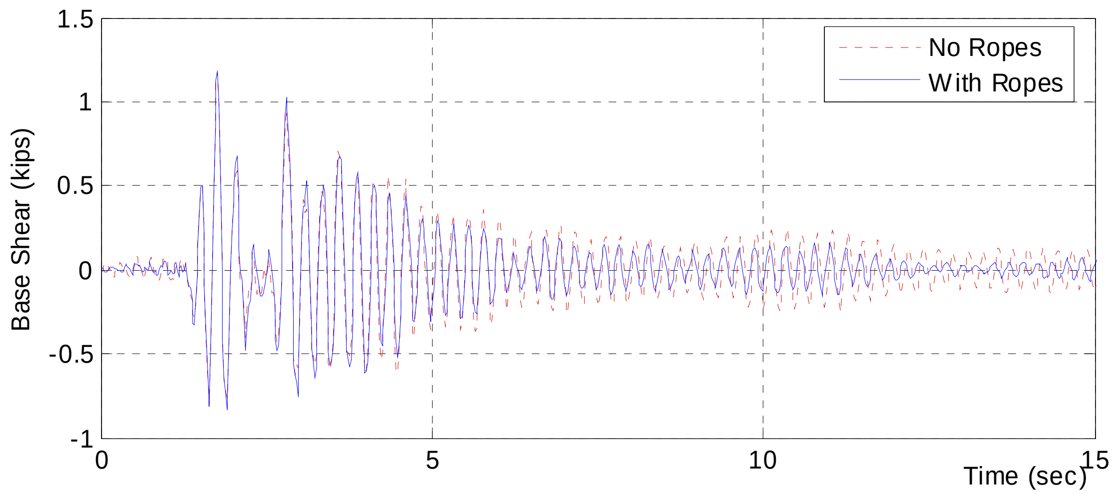


a) Comparison of NR-1-30 and NR-2-30

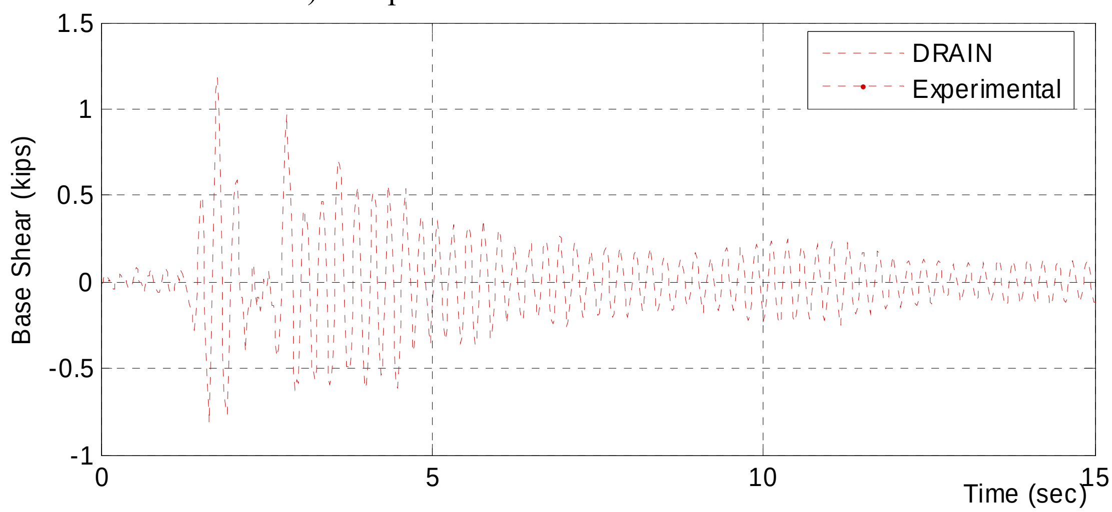


b) NR-1-30 Results Shown Separately for Clarity

Figure 5. 51: Roof Displacement Comparison: NR-1-30 and NR-2-30



a) Comparison of NR-1-30 and NR-2-30



b) NR-1-30 Results Shown Separately for Clarity

Figure 5. 52: Base Shear Comparison: NR-1-30 and NR-2-30

5.7.2 TESTS NR-1-180 AND NR-2-180

Tests NR-1-180 and NR-2-180 were the primary basis for evaluating the effect of adding rope devices to the 1:6-scale frame for the purpose of improving the performance of the frame subjected to ground motion representing a design earthquake event. Performance of the structure was evaluated based on the level of yielding experienced by the frame and the residual drift of the frame.

The primary basis of performance improvement due to rope devices was the comparison of average residual drift measured at the diaphragm levels, reported in Table 5.4. The average reduction in drift from Test NR-1-180 to Test NR-2-180 was calculated and is reported in the final column of the table. Residual drift measured after Test NR-1-180 (No Ropes) was observed to be reduced by 67% in Test NR-2-180 (with Ropes). The corresponding percent-residual roof drift with respect to the overall frame height was 0.7% and 0.2% for Tests NR-1-180 and NR-2-180, respectively. The residual drift results indicate a drastic improvement to the performance of the 1:6-scale frame after rope devices were added.

Table 5. 4: Average Residual Drift Comparisons: NR-1-180 and NR-2-180

Diaphragm Level	NR-1-180 (in.)	NR-2-180 (in.)	Average Reduction
Floor	0.18	0.06	67%
Roof	0.36	0.12	67%

Corroborating evidence of the drastic improvement to frame performance was found using strain data, in which yielding experienced by the roof and floor beams was measured directly. Strain was measured at 0.75 inches from the edge of the flange plates, corresponding to one-half of the beam-member depth. Yielding was observed visually at the strain gage locations, indicating that the gages were installed where plastic hinging occurred in the roof and floor beams. Representative measurements of tensile strain related to bending for the bottom of the floor beam and the bottom of the roof beam are shown in Figures 5.53 and 5.54, respectively. Yield strain, corresponding to 2,000 microstrain (mμ) for steel with a yield point equal to 50 ksi, was observed in both tests. The maximum recorded yield strain of the floor beam in the frame tested without ropes was 6,620 mμ. When ropes were added, the maximum strain recorded was 3,100 mμ, corresponding to a 53% percent reduction. The strain at the roof was also reduced, but to a lesser extent. Maximum strain recorded in the roof beam of the frame without ropes was 2,500 mμ, reduced by only 16% to 2,100 mμ when ropes were added. Residual strain was also reduced by the addition of ropes. Residual strain in the floor beam was approximately 1,350 mμ, compared to no residual strain observed in the frame with rope devices added. At the roof, recorded residual strain was reduced by 50%. Averages of recorded maximum beam strain and residual strain were calculated for the floor and roof beams and are presented in Table 5.5.

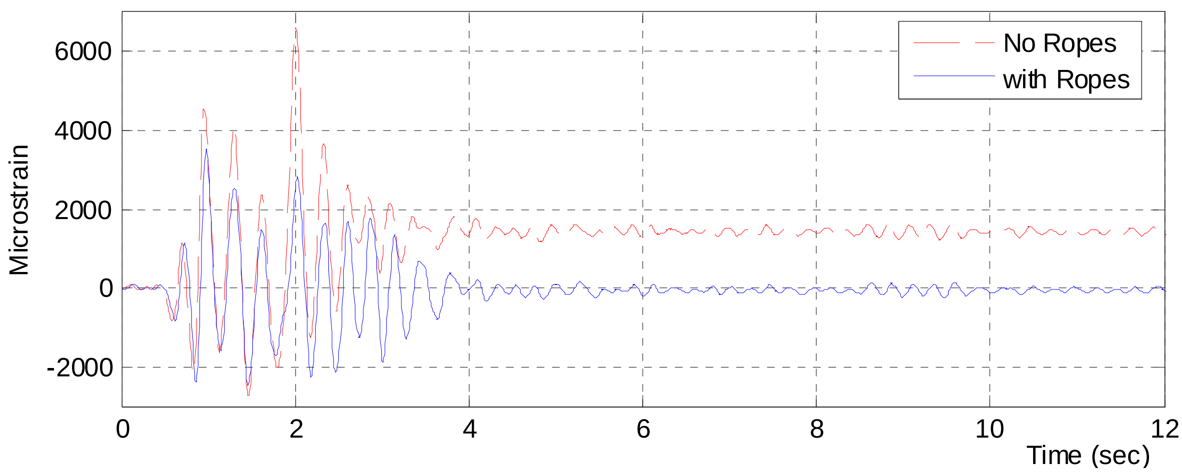


Figure 5. 53: Strain Comparison at North-Floor-Bottom: NR-1-180 and NR-2-180

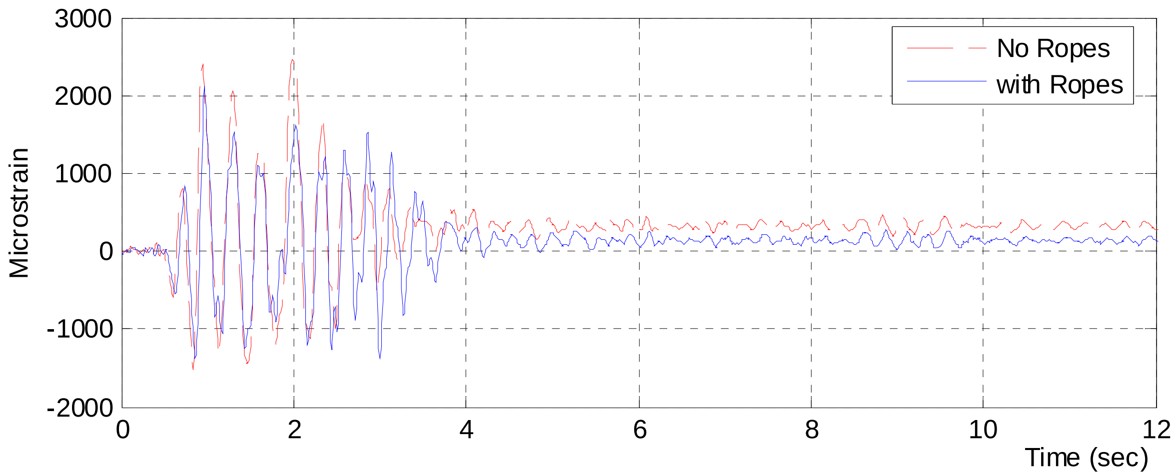


Figure 5. 54: Strain Comparison at North-Roof-Bottom: NR-1-180 and NR-2-180

Table 5. 5: Average Maximum and Residual Strain: NR-1-180 and NR-2-180

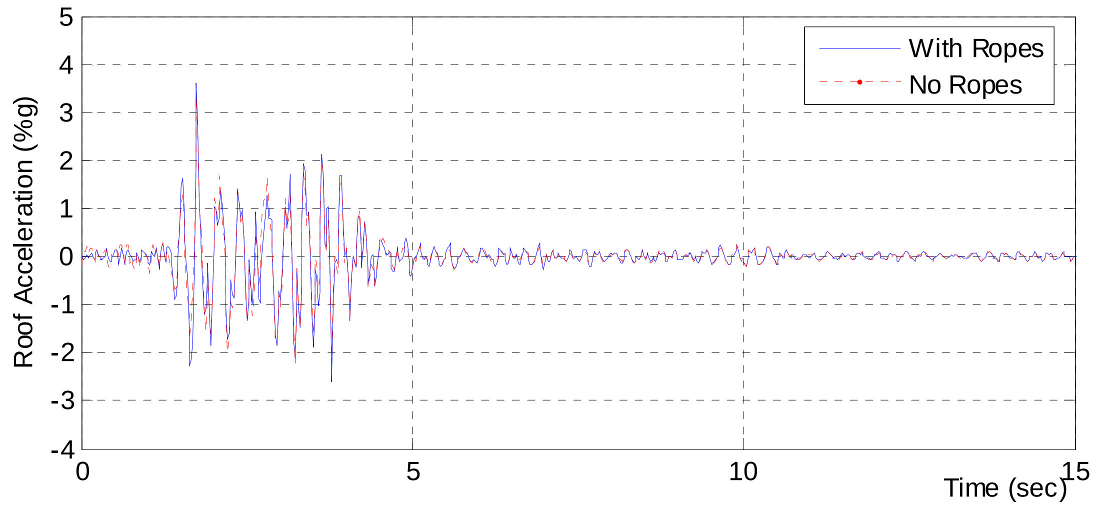
Level	**Maximum Strain**			**Residual Strain**		
	NR-1-180 (mμ)	**NR-2-180 (mμ)**	**Average Reduction**	**NR-1-180 (mμ)**	**NR-2-180 (mμ)**	**Average Reduction**
Roof	2834	2127	21%	366	147	60%
Floor	6949	4053	42%	3050	391	87%

Although maximum displacement of the frames could not be determined from acceleration data with accuracy during Tests NR-1-180 and NR-2-180, relative maximum displacement between tests was evaluated indirectly based on the following:

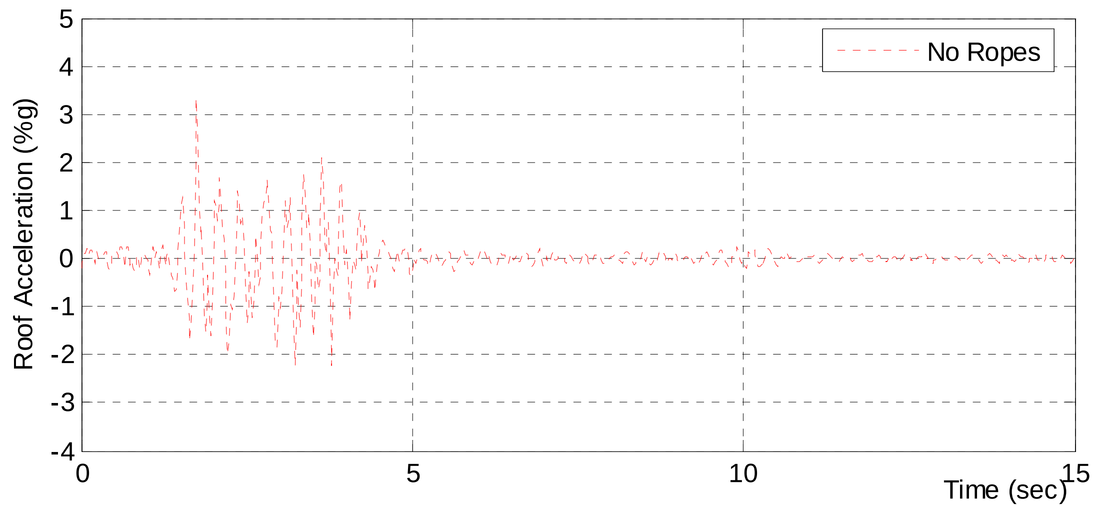
- Magnitude of bending strain in the beams is a direct indication of the magnitude of lateral frame drift.
- Strain was measured in the same locations for both frames.
- The fabrication process was identical for both frames and resulted in frames that were observed through testing to have nearly identical stiffness and dynamic characteristics. It is therefore assumed that relative rotation of the roof and floor beams results in similar relative drift.
- The difference in relative strain values was consistent between Tests NR-1-180 and NR-2-180 for all strain measurements.
- Although strain at the base of the frame columns was not measured, the contribution of rotation at the base of the columns to overall frame drift was assumed to be similar for both frames.

An exact reduction of maximum displacements could not be made based on strain data. However, based on general observation of the relative strain magnitudes, it was considered reasonable to conclude that the addition of the ropes resulted in a significant reduction to the maximum displacement of the frame, particularly in light of the reduction to maximum residual drifts, which were measured directly.

Comparisons of roof acceleration traces and total base shear for Tests NR-1-180 and NR-2-180 are shown in Figures 5.55 and 5.56 respectively. Traces of the acceleration at the roof were very similar. Peak values recorded during Test NR-2-180 were between 5% and 8% greater than those recorded during Test NR-1-180. The similarity in the shape of the traces indicated that the general dynamic response characteristics of the frame were not changed significantly as a result of adding rope devices. Maximum base shear was increased by merely 7% from 5.9 kips to 6.3 kips with the addition of ropes during the initial pulses of ground motion. Further, the comparison of base shear traces subsequent to the initial pulses indicated a slight reduction in total base shear from Test NR-1-180 to Test NR-2-180.

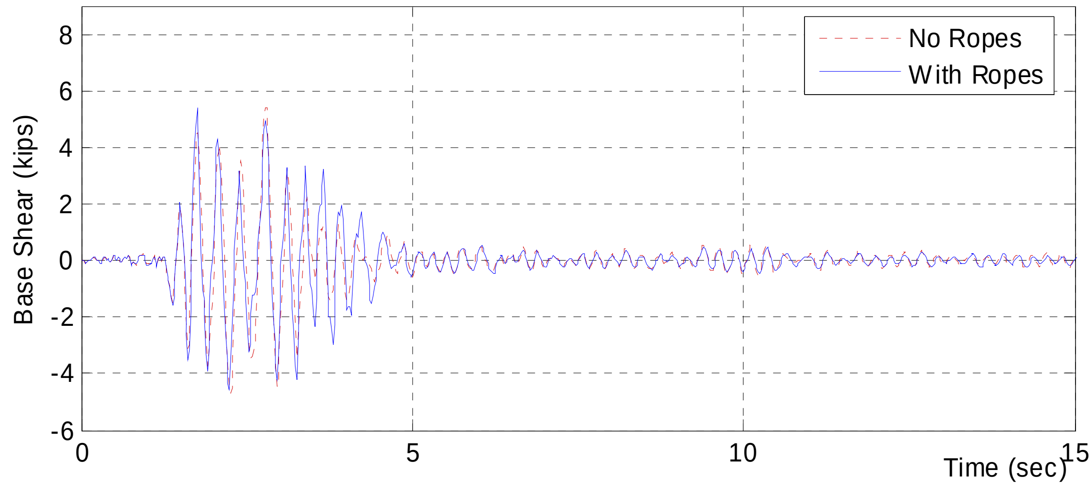


NR-1-180 and NR-2-180

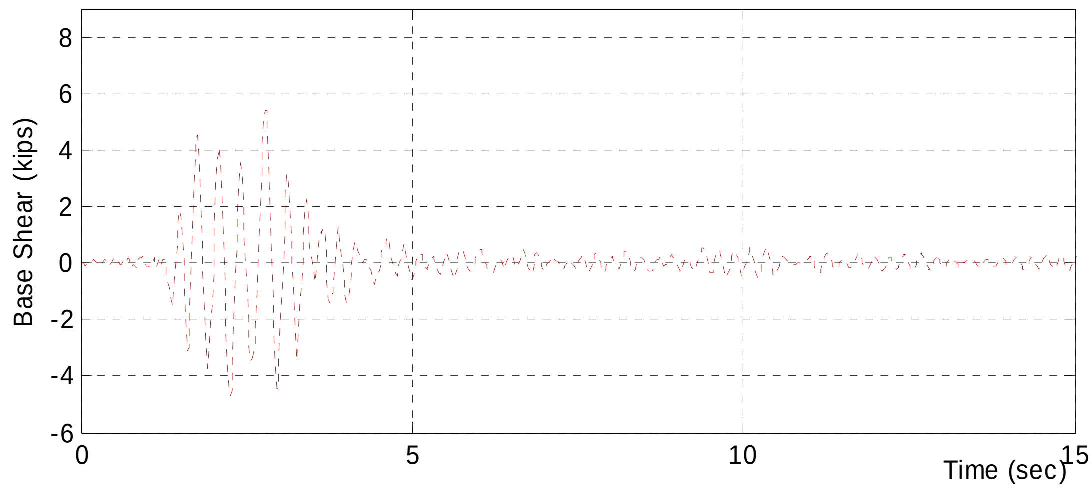


NR-1-180 Results Shown Separately for Clarity

Figure 5. 55: Roof Acceleration Comparison: NR-1-180 and NR-2-180



NR-1-180 and NR-2-180



NR-1-180 Results Shown Separately for Clarity

Figure 5. 56: Base Shear Comparison: NR-1-180 and NR-2-180

A closer examination of the comparisons of roof acceleration and base shear traces from the initiation of ground motion to 5 sec adds depth of understanding to the influence of the rope devices (Figures 5.57 and 5.58). The acceleration and base shear traces are slightly higher for the frame tested with ropes during the initial pulse. However, the acceleration and base shear values at subsequent peaks were smaller for the frame tested with ropes, indicating that energy was dissipated by the ropes. Additionally, no spike in the acceleration or base shear traces was observed as the ropes became effective. Both phenomena were attributed to rope response observed during the conditioning of the ropes. Hysteresis of the rope response was determined to be responsible for energy dissipation, while a gradual increase in rope stiffness upon loading, termed “hyper-elastic” response, resulted in stiffness being added without causing a shock-load to the system.

Supporting evidence was observed through visual observation of the test. When reviewing side-by-side synchronized video of the tests at one-half speed, the ropes appear to slowly engage and arrest the motion of the Frame 2, compared to video of the tests conducted of Frame 1. As displacement of the frame returns to zero, the ropes do not appear to act as elastic springs, driving the frame through the point of zero displacement. Rather, the ropes returned to initial conditions through a highly reduced stiffness, and disengaged completely prior to the frame reaching its relative initial position with respect to the shaking table.

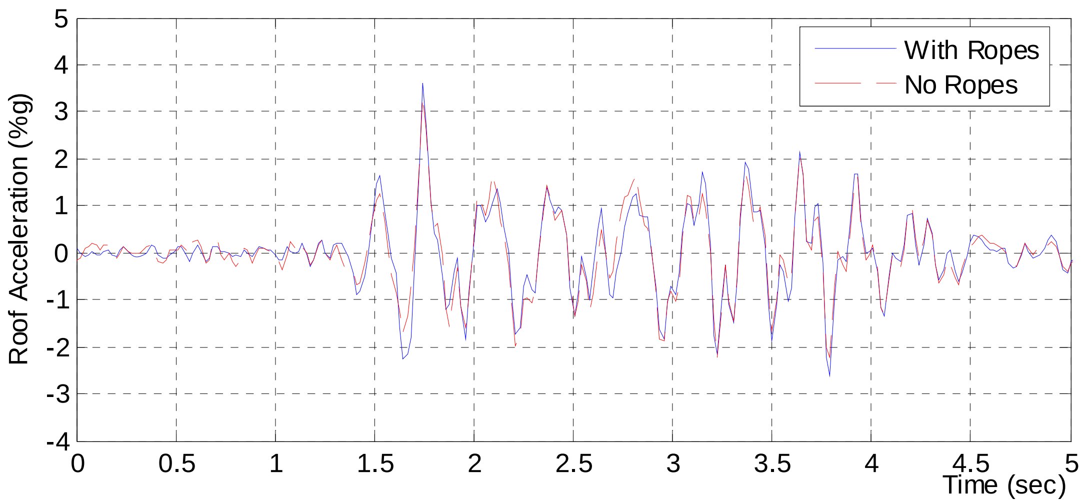


Figure 5. 57: Comparison of Roof Acceleration between 0 and 5 sec: NR-1-180 and NR-2-180

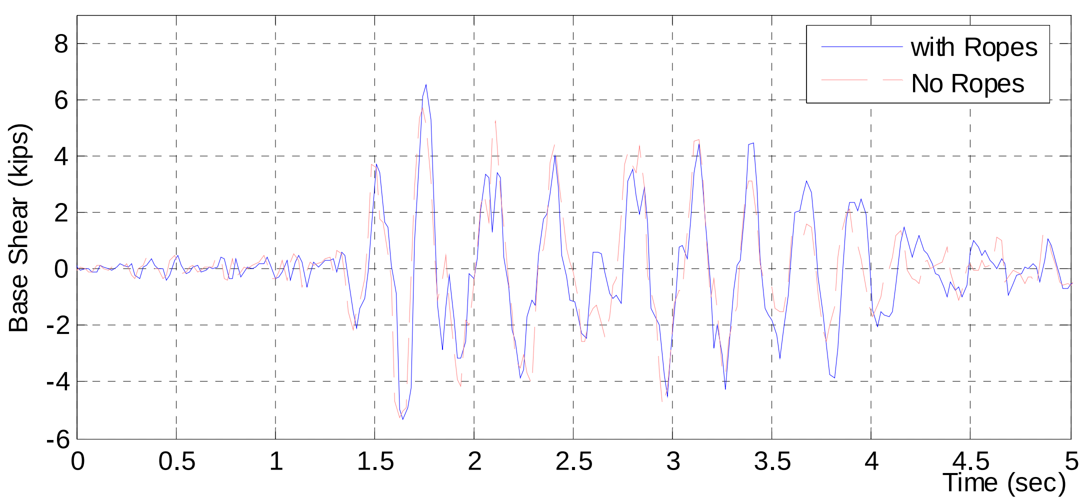


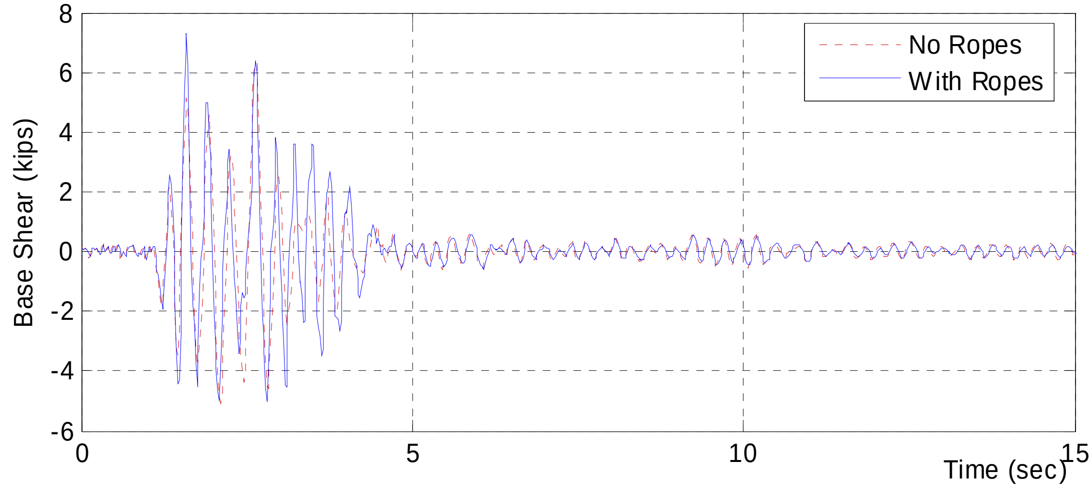
Figure 5. 58: Comparison of Base Shear between 0 and 5 sec: NR-1-180 and NR-2-180

5.7.3 TESTS NR-1-220 AND NR-2-220

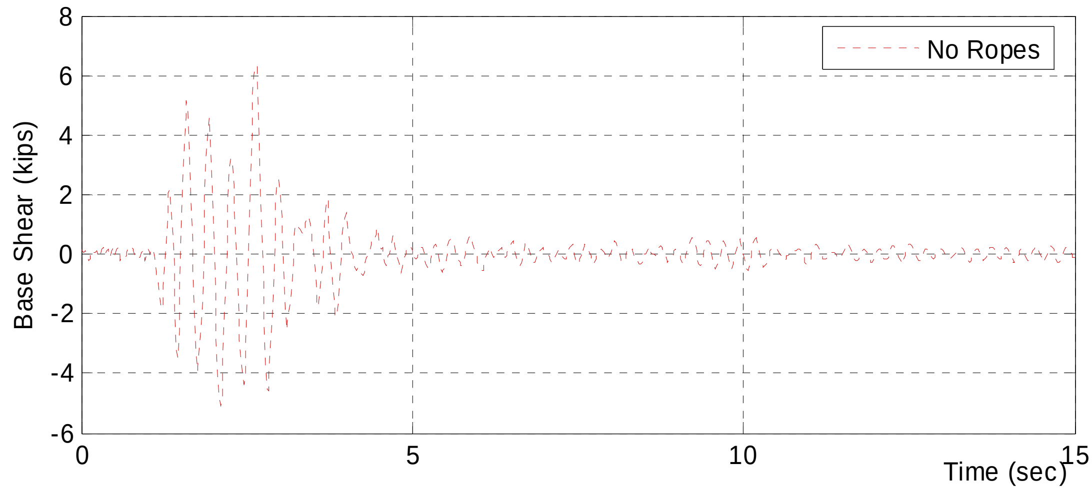
Tests NR-1-220 and NR-2-220 were conducted to investigate repeatability of 180% Northridge ground-motion test results at a higher level of ground motion. These tests were not originally planned, and were considered supplemental to the 30% and 180% ground motion tests. Residual drift and base shear comparisons are shown in Figure 5.59 and Table 5.6, respectively, and further validate the assertion that synthetic fiber ropes improved the performance of the 1:6-scale moment frame when subjected to large ground-motion input.

Maximum base shear was greater by 18% for Test NR-2-220 when compared to Test NR-1-220. An increase in the relative magnitude of base shear with ropes added, compared to the 180% ground-motion tests, was expected due to the initial conditions of Frame 1 and Frame 2 prior to Tests NR-1-220 and NR-2-220. Frames used for Tests NR-1-220 and NR-2-220 were the same frames used for NR-1-180 and NR-2-180, respectively. Initial conditions for both frames included residual drift from prior tests. Therefore onset of yielding in Test NR-1-220 occurred at a relatively lower level of displacement from the initial condition in the direction of residual drift, when compared to Test NR-2-220. The relatively larger increase in base shear between Frame 1 and Frame 2 (from 8% for 180% tests to 18% for 220% tests) was attributed in part to softening of the frame response in Test NR-1-220 at a lower level of displacement. In addition, the ropes continued to add stiffness to the frame response after hinging in the frame occurred. Therefore, at higher levels of post-yield displacement, the rope device contributed a higher percentage of the total base shear. The maximum rope force for Test NR-2-220 was 2.7 kips, representing 22% of the total base shear, 8.7 kips, whereas the maximum rope force for Test NR-2-180 was 1.3 kips, representing 15% of the total base shear, 6.2 kips.

Other than maximum base shear values, consistency of 220% ground-motion tests with results of 180% ground-motion tests was observed for base shear and residual drift. In general the analysis of 180% ground-motion test results are applicable to the 220% ground-motion test results.



NR-1-220 and NR-2-220



NR-1-220 Results Shown Separately for Clarity

Figure 5. 59: Base Shear Comparison: NR-1-220 and NR-2-220

Table 5. 6: Average Residual Drift Comparisons: NR-1-220 and NR-2-220

Diaphragm Level	NR-1-220 (in.)	NR-2-220 (in.)	Average Reduction
Floor	0.57	0.20	65%
Roof	1.02	0.38	63%

5.8 COMMENTARY ON PERFORMANCE OF ROPE DEVICES

After Test NR-2-180, ropes were investigated for damage. No damage to the ropes was evident, generally indicated by exposed rope core, eye-splice pull-out, or fraying surface. The North-Bottom and South-Top ropes exhibited a small amount of permanent deformation equal to approximately 0.25 in. This was determined by tightening the threaded adjustment devices while monitoring the load cell and the number of turns required to return to 80 lb of tension in the rope. Four turns of the nut were required on the UNC-16 threaded rod. The rope condition was re-set from 80 lb prior to the NR-2-220 test. In a real structure, it would be necessary to re-set the rope condition after large excursions were experienced.

Overall, the addition of the ropes resulted in significant reduction to yielding and residual drift of the 1:6-scale frame, while only contributing slightly to the maximum total base shear. This was attributed to the hyper-elastic loading curve and reduced stiffness of the unloading curve observed in the rope devices throughout this study. These characteristics were the driving factor for the proposal of synthetic fiber ropes for this specific application. Although many questions about the suitability of synthetic fiber ropes for structural use need to be addressed, these tests tend to validate the viability of devices with the response characteristics of synthetic fiber ropes for use in improving seismic performance of steel moment frames.

5.9 SUMMARY OF EXPERIMENTAL RESULTS

Results of the performance modification to the 1:6-scale frame by adding rope devices are as follows:

- Response of low-amplitude motion, consistent with service wind loading or small-scale ground motion, was not affected by the ropes.
- Initial rope condition, necessary to provide intended response modification to a frame subjected to large-scale ground motion, did not affect low-amplitude motion of the frame.
- Residual lateral drift of the frame at the roof was reduced by 67% and 63% when ropes were added for 180% ground-motion and 220% ground-motion tests respectively.

- Maximum total base shear of the frame was increased by 8% and 18% when ropes were added for 180% ground-motion and 220% ground-motion tests respectively.
- Residual and maximum roof and beam strains were observed to be significantly reduced in frame tests conducted with ropes for the 180% and 220% ground-motion tests.
- Based on residual and maximum roof and beam strains and residual deformation measurements, maximum displacements were determined to be significantly reduced in frame tests conducted with ropes for the 180% and 220% ground-motion tests.
- Ropes provided consistently reliable response characteristics throughout testing.
- Performance of the 1:6-scale frame was significantly improved by the addition of the rope devices.