CHAPTER 2

Initial Experimental Testing Program

2.1 OVERVIEW OF INITIAL EXPERIMENTAL TESTING PROGRAM

Amsteel II, a double-braided rope constructed from high-molecular-weight polyethylene (HMWPE) fibers, made by Sampson Rope Company, was selected for the initial experimental testing program, based on results from Hennessey (2003). The initial experimental program consisted of a series of dynamic experiments including component testing of the ropes, 1:3-scale tests with a steel portal frame, and quasi-static ultimate-load tests. Component testing was first conducted to isolate the behavior of the ropes when subjected to varying sinusoidal loading inputs within the range of anticipated structural displacements and velocities (Section 2.2). A 1:3-scale steel moment frame was then designed and constructed. The steel frame was tested with and without rope devices installed across the diagonal using load-controlled sinusoidal lateral loading of varying amplitude and frequency as described in Section 2.3. Quasi-static axial rope tests were conducted on ropes used during the 1:3-scale tests and are presented in Section 2.4.

2.2 DYNAMIC AXIAL ROPE TEST

2.2.1 OVERVIEW

Dynamic axial rope tests were conducted to determine the dynamic response of the ropes when forced through elongations that approximate elongations anticipated in real structures, at velocities that approximate velocities anticipated in real structures during a design earthquake, within the limitations of the available testing equipment. The test specimen group consisted of two 0.5-in.-diameter Amsteel-II ropes with nominal lengths of 8 ft. The ropes were previously used in drop tests by Hennessey (2002) and retain the designations HH and GG, as assigned by Hennessey are retained herein. Neither rope was pre-cycled prior to being tested by Hennessey. The primary difference in the previous testing of the ropes was the drop height. The drop heights used in the previous experiment were 44 in. and 56 in. for ropes HH and GG, respectively.

The purpose of this test program was threefold. First, it was of particular interest to determine the relative end-to-end velocity-related characteristics of the rope when subjected to velocities within the range of anticipated structural velocities. Secondly, it was of interest to verify the nonlinear stiffness characteristics of the ropes studied by Hennessey (2002) when subjected to displacements and velocities expected in structures excited by earthquake-induced ground motions. Finally, it was of interest to observe the peak load in the ropes as well as the energy dissipated by the rope at the slack-to-taut transition. The intent of this study was to quantify the contributions of the velocity-related, displacement-related, and snapping-related responses to the overall response of the rope at realistic structural velocities and displacements.

2.2.2 TESTING FRAME

Component tests were conducted in the Virginia Tech Structures and Materials Research Laboratory using the test frame shown in Figures 2.1 through 2.4. The test frame used was composed of two 16 ft 0 in.-tall W21x68 steel columns fixed at the base to the laboratory reaction-floor beams at 8 ft 0 in. on center. Two 8 ft 0 in.-long W24x94 steel beams spanned between the columns at approximately 13 ft. above the reaction floor, and were bolted to each flange of the columns. A 55,000-lb-capacity MTS dynamic actuator was hung from the W24x94 steel beams at the midpoint, such that the load from the actuator was equally distributed between the two beams. The actuator was positioned directly above a beam in the reaction floor. Two three-plate steel fixtures were fabricated. To accommodate the allowable specimen length, equal approximately 4 ft, the rope was passed once through the fixture attached to the actuator, creating a two-part line. One was bolted to the actuator and the other was bolted to the reaction beam directly below the actuator. These fixtures provided a pin attachment for the rope at each reaction point.

It was assumed in the design of the load frame that the elastic response of the frame itself would be extremely small and could therefore be neglected throughout the test. A wire potentiometer was used to check this assumption. The potentiometer was calibrated and placed such that the relative movement between the reaction floor and the W24 actuator support beams could be measured. A 10,000-lb load was applied quasi-statically. The potentiometer indicated a shortening of 0.0015 in. between the reference points at a load of 10,000 lb, was small enough to be neglected.

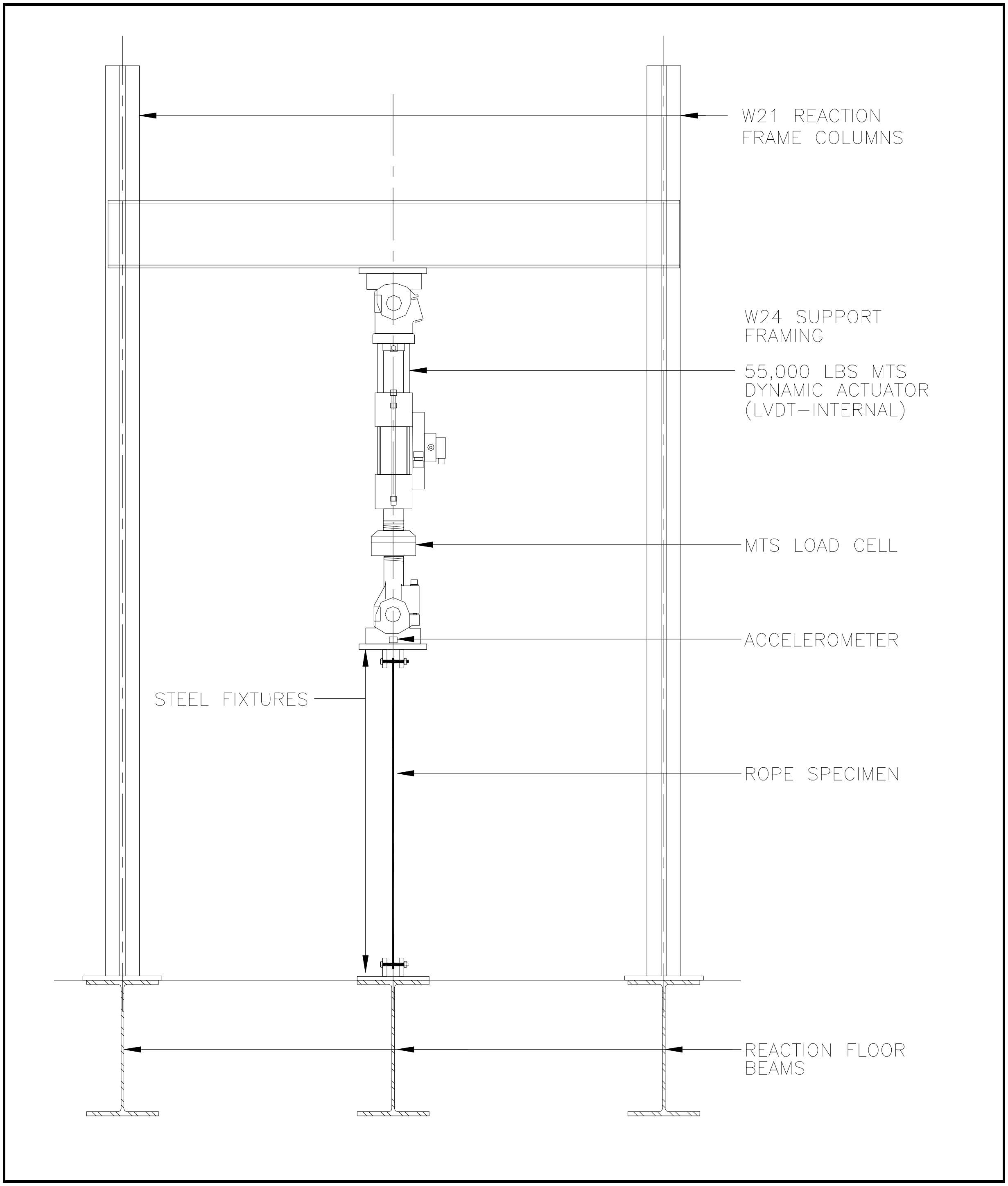


Figure 2. 1: Load Frame Used for Axial Rope Tests

Figure 2. 2: Photograph of Load Frame for Axial Rope Tests

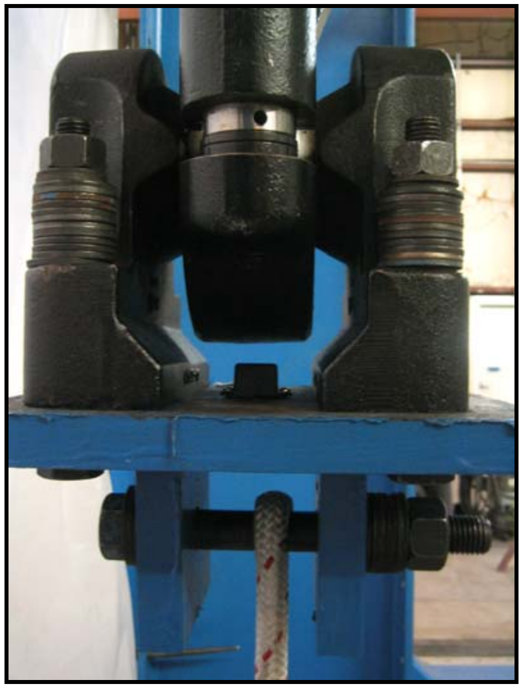


Figure 2. 3: Photograph of Rope-to-Actuator Connection

Figure 2. 4: Photograph of Rope-to-Reaction-Floor Connection

2.2.3 LOADING PROTOCOL

The test specimens were first subjected to a quasi-static load of 12,000 lb (6,000 lb per part of line) and then returned to zero load. The rope was then pulled to a touch load equal to 50 lb and subjected to a series of seven displacement-controlled loading functions having the following form for three complete cycles each:

$$y(t)_i = y_i \sin \omega_i t \tag{2-1}$$

In this function, $y(t)_i$ is the displacement with respect to time in inches, y_i is the amplitude of the sinusoidal loading in inches (Table 2.1), ω_i is the frequency of oscillation in radians per second , t is time in seconds, and "i" is incremented from one to seven. This loading function was chosen because it allowed for a simple conversion from measured displacement to velocity and provides continuous dynamic loading which was easily implemented and adjusted using the available controller. Figure 2.5 is a graphical depiction of the complete dynamic loading protocol. Values of amplitude and frequency for each increment are shown in Table 2.1.

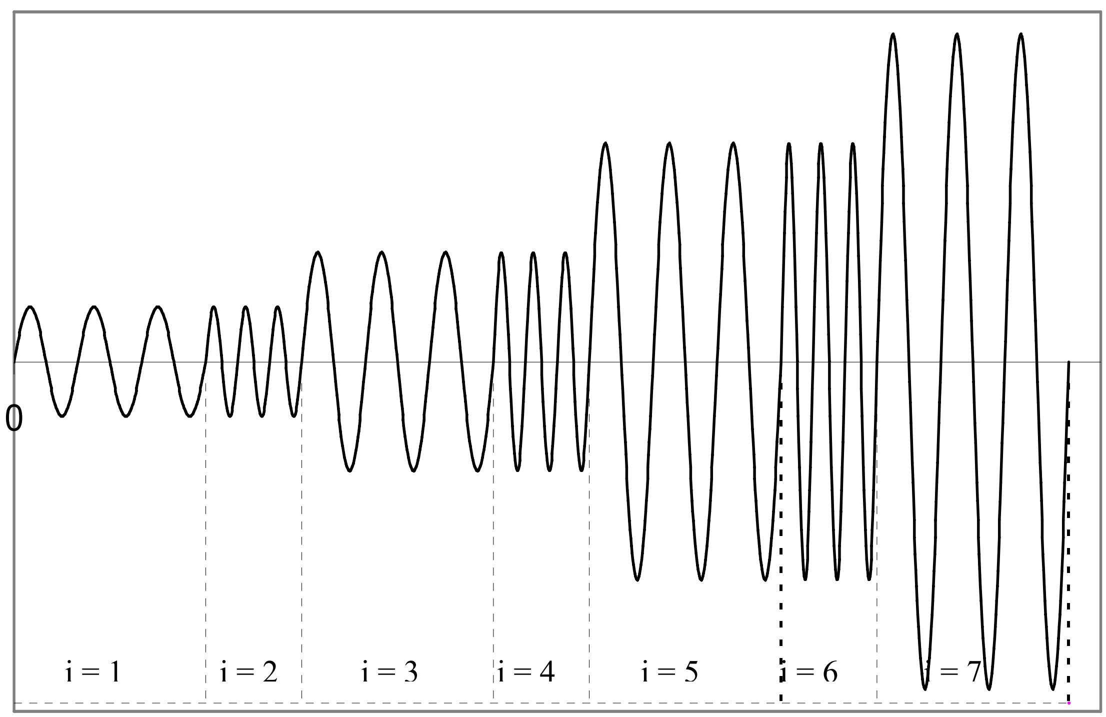


Figure 2. 5: Displacement History for Axial Rope Tests

Table 2. 1: Amplitude and Frequency of Loading Function for Axial Rope Tests

Displacement Function: $y(t)_i = y_i \sin w_i t$					
i	**y_i (in.)**	**w_i (rad/sec)**	**Frequency (Hz)**	**Period (sec)**	**Cycles**
1	0.25	2π	1	1.0	3
2	0.25	4π	2	0.5	3
3	0.5	2π	1	1.0	3
4	0.5	4π	2	0.5	3
5	0.75	2π	1	1.0	3
6	0.75	4π	2	0.5	3
7	1.0	2π	1	1.0	3

2.2.4 INSTRUMENTATION

To obtain the desired information, displacement and load were measured continuously. The MTS actuator used is equipped with an internal Linear Variable Differential Transformer (LVDT) and a 55,000-lb-capacity load cell. In addition, an accelerometer was fixed to the steel fixture at the loading end of the rope to provide a means of verifying the displacement data obtained from the *MTS* system during the dynamic load history.

The signals transmitted from all three devices were converted in real-time and recorded directly by a Micromeasurements System 6000 data acquisition device. An optimum recording rate was determined to be 200 records per second, corresponding to 0.005-second time increments for data recorded during all tests.

The MTS LVDT was calibrated using a dial-type stand extensometer. The range of the LVDT is +/- 3.5 inches. The load cell was also calibrated by an MTS technician using a load cell calibrated at the National Institute of Standards and Technology (NIST).

2.2.5 AXIAL ROPE TEST RESULTS

The dynamic axial rope tests were conducted to observe the general response characteristics of Amsteel II ropes subjected to dynamic loading cycles within the range of anticipated structural displacements and velocities. Several key observations were made during testing which were useful in determining the type of finite element formulation best suited for approximating the response of the rope devices. The maximum load previously experienced by a particular rope was observed to be the most influential variable on the response of the rope. Hysteresis of the response of the ropes was observed to be relatively stable through multiple cycles of loading if the rope was conditioned. The end-to-end velocity of the rope within the testing range of loading was shown to have little effect on the response. Energy loss at the slack-to-taut transition was observed to be small.

Although the exact level of expected permanent elongation in the rope was not quantified in previous tests, significant permanent elongation was observed in ropes upon initial loading. An initial quasi-static load equal to the maximum load to be applied to the ropes throughout the dynamic axial rope test was applied to the ropes to determine the amount of permanent elongation experienced by the ropes, prior to applying the cyclic loading protocol. A typical load versus displacement plot of the full loading sequence is shown in Figure 2.6. The permanent elongation during the static load cycle of ropes HH and GG was equal to 0.8 in. and 0.9 in. respectively. If these ropes were used in a structural application, permanent elongations of this magnitude in the first cycle of loading would render the ropes ineffective for subsequent loading cycles. Hence, in a seismic application the ropes would contribute to the response of the frame only during the first large excursion. Therefore, it is necessary that ropes used for structural applications be preloaded, or conditioned, to be effective. Observations of subsequent dynamic loading cycles indicated that the response of the ropes through multiple cycles remained relatively stable, incurring limited permanent deformation, up to loading cycles above the conditioning load (Figure 2.6).

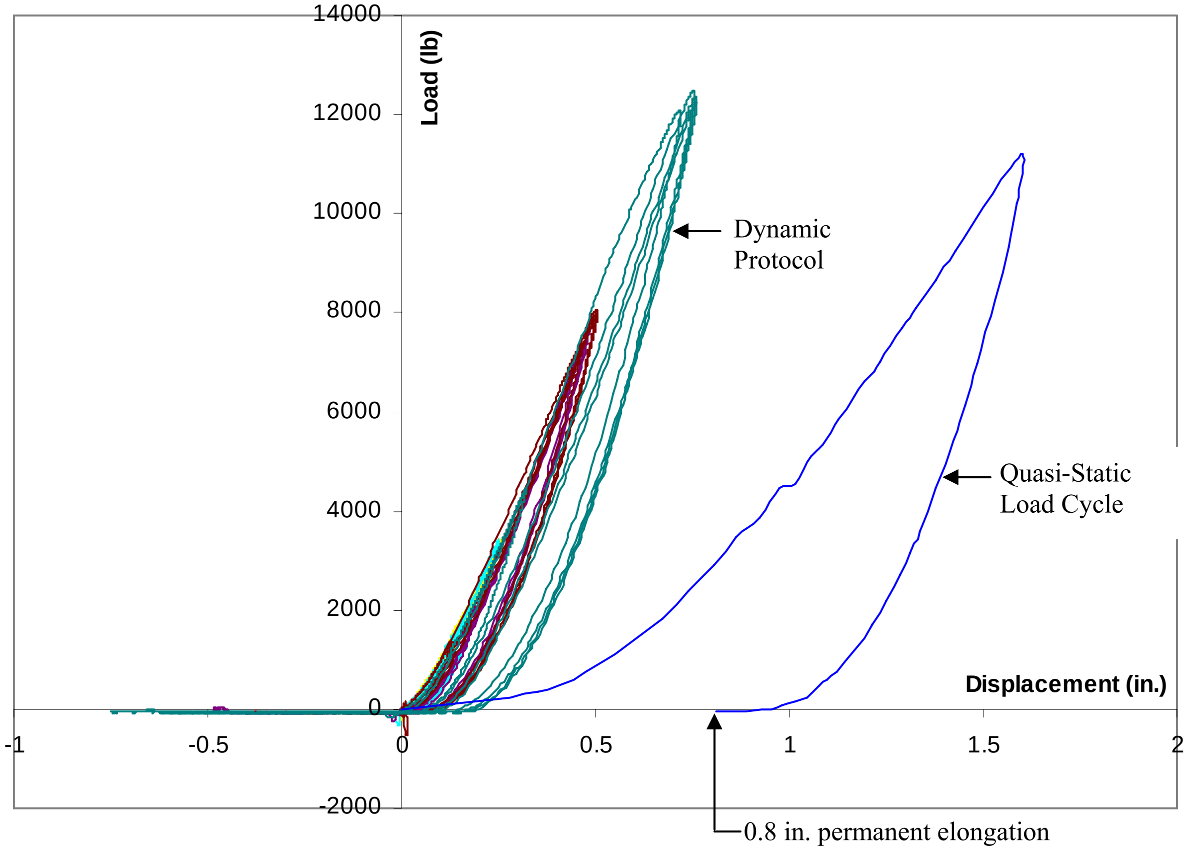


Figure 2. 6: Response History of Rope HH

Velocity changes were compared between loading cycles at differing frequencies, but with the same displacement amplitude (Figure 2.7). The response of the rope due to different loading frequencies appeared to be similar. Therefore, it was concluded that the response of the ropes is not heavily dependent on velocity within the range of loading. In reference to Figure 2.7, it should be noted that a small amount of permanent elongation occurs between the first five loading cycles (frequency of loading = 1 Hz) and the second group of loading cycles (frequency of loading = 2 Hz). A perfect comparison was therefore difficult to make.

In summary, the objective of this test was to determine general characteristics of the rope behavior that would provide practical information regarding the use of Amsteel II ropes in structural applications, as well as lead to an appropriate model to be used for the analysis of structures with ropes. The results showed that the ropes must be conditioned by preloading above the maximum anticipated rope load. Upon being conditioned, the ropes exhibit primarily displacement based response in loading and unloading. The cyclic response history showed that some energy dissipation occurs and appeared stable through several loading cycles.

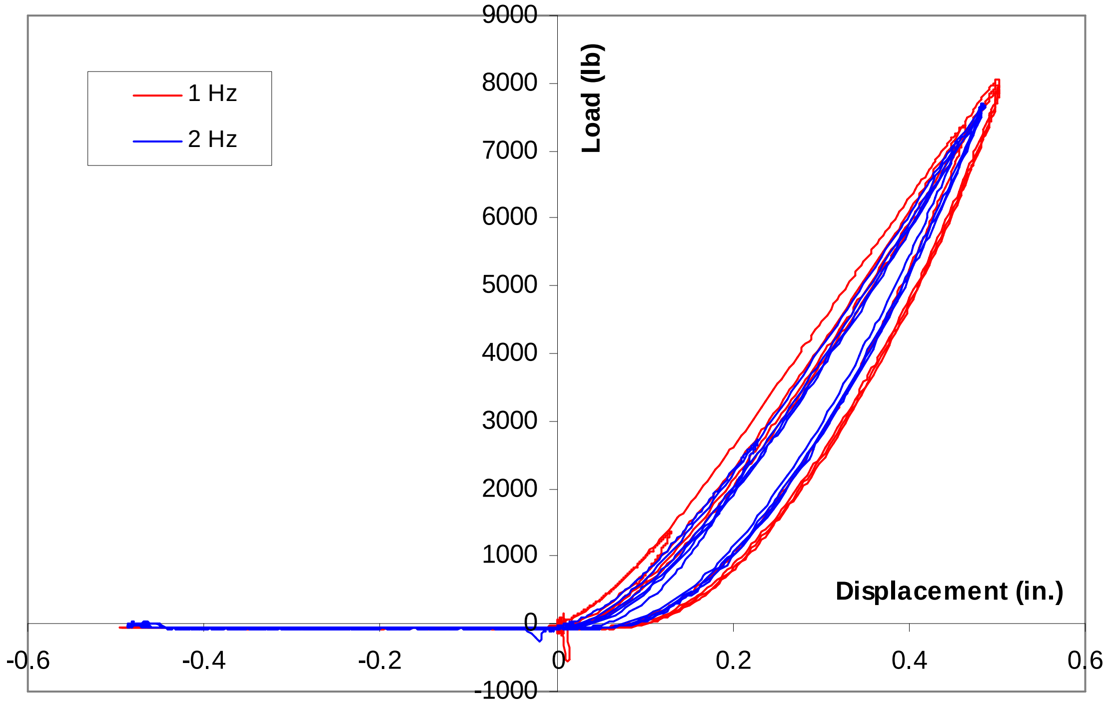


Figure 2. 7: Comparison of 1-Hz and 2-Hz Loading Cycles for Rope HH (y_i= 0.5 in.)

2.3 1:3-Scale Frame Test

2.3.1 Overview

An experimental study was conducted to determine the change in the dynamic response of a steel moment frame after adding Amsteel II ropes in an X-brace configuration across the diagonals. The purpose of this test program was to quantify the change in the elastic response of the steel moment frame with ropes added when subjected to dynamic sinusoidal load-controlled loading. Overall frame stiffness, energy dissipation, displacements, and maximum rope force were of interest. These parameters were monitored and recorded for both frame configurations and for all loading conditions. Comparisons of the test frame without ropes were made to the test frame with ropes based on these parameters to gain a greater understanding of the interaction between the ropes and the steel frame.

A 1:3-scale model of a steel moment frame was designed and its geometry was adjusted slightly for testing constraints. A single frame was constructed and used for all tests. The frame was tested in two basic configurations: with ropes and without ropes.

Testing of the 1:3-scale frame was broken into five test groups: static frame tests without ropes, dynamic frame tests without ropes, dynamic frame tests with ropes, dynamic frame tests with ropes and 1000-lb pre-tension in the ropes, and a loading sequence with and without ropes beyond the elastic strength of the frame. A key to the abbreviations for specific tests is shown in Figure 2.8. Table 2.2 provides a brief description of each test series and the reference section in which each test series is detailed. A complete list of all tests is presented in Table 2.3.

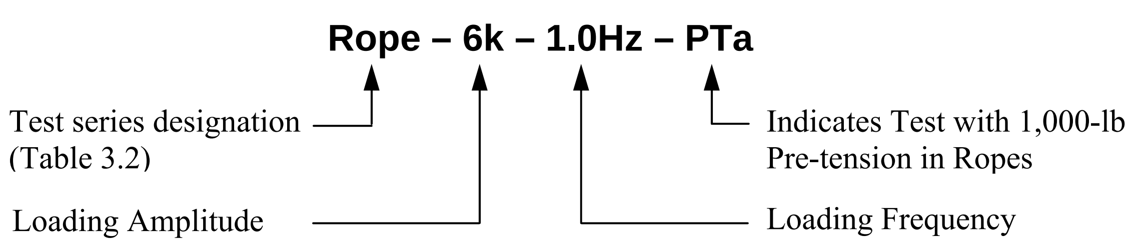


Figure 2. 8: Typical Convention for Test Designations

Table 2. 2: Test Series Designations

Tests Series Description	Test Group Designation	Reference Section
Static frame tests without ropes	Static	2.3.8.1
Dynamic frame tests without ropes	Frame	2.3.8.2
Dynamic frame tests with ropes	Rope	2.3.8.3
Dynamic frame tests with ropes and with 1000 lb preload in ropes	Rope	2.3.8.4
Loading sequence with and without ropes beyond the elastic capacity of the frame	I.S.-Frame, I.S.-Rope	2.3.8.5

2.3.2 DEVELOPMENT OF STEEL MOMENT FRAME

The dimensions and sections for the steel moment frame were chosen based on similitude with a prototypical moment frame of a low-rise office structure, research laboratory limitations, and availability of materials. An illustration and photograph of the test frame are shown in Figures 2.9 and 2.10. Similitude principles are discussed in Appendix A.

The dimensions of the frame were determined, considering a prototypical story height of 13 ft 6 in., and center-to-center column dimension of 30 ft 0 in. Using similitude, the test specimen dimensions were found by simply dividing the prototype dimensions by the length scale factor, 3.0. The result is a frame with height of 4 ft 6 in. and center-to-center column dimension of 10 ft 0 in. The length of the diagonal was increased by 2 ft 0 in., since the addition of the load cell would shorten the length of the rope by that amount. The beam was lengthened to obtain the required diagonal length, resulting in a center-to-center column dimension equal to 11 ft 8 in. The resulting length of the diagonal, less the length of the load cell, was approximately 12 ft 6 in, which is slightly greater than one-third of the prototype diagonal length, 33 ft 0 in.

Table 2. 3: List of 1:3-scale Frame Tests

Test No.	Test Group	Amp.	Freq.	PT	Load Cycles
1	Static -	8k			1
2	Static -	6k			1
3	Frame -	3k -	0.5Hz		10
4	Frame -	3k -	0.75Hz		10
5	Frame -	3k -	1.0Hz		10
6	Frame -	6k -	0.5Hz		10
7	Frame -	6k -	0.75Hz		10
8	Frame -	6k -	1.0Hz		10
9	Rope -	3 k -	0.5 Hz		10
10	Rope -	3 k -	0.75 Hz		10
11	Rope -	3 k -	1.0 Hz		10
12	Rope -	6 k -	0.5 Hz		10
13	Rope -	6 k -	0.75 Hz		10
14	Rope -	6 k -	1.0 Hz		10
15	Rope -	6 k -	1.0 Hz -	PTc	5
16	Rope -	6 k -	1.0 Hz -	PTd	5
17	Rope -	8.5 k -	1.0 Hz		6
18	Rope -	10 k -	1.0 Hz		5
19	Rope -	8.5 k -	1.0 Hz -	PTe	5
20	Rope -	10 k -	1.0 Hz -	PTf	5
21	I.S.-Rope -	8.5k -	0.75Hz -	PTg	5
22	I.S.-Frame-	8.5k -	0.75Hz		5
23	I.S.-Rope -	10k -	0.75Hz -	PTh	5
24	I.S.-Frame-	10k -	0.75Hz		5
25	I.S.-Rope -	11k -	0.75Hz -	PTi	5
26	I.S.-Frame-	11k -	0.75Hz		5
27	I.S.-Rope -	12k -	0.75Hz -	PTj	5
28	I.S.-Frame-	12k -	0.75Hz		5
29	I.S.-Rope -	14k -	0.75Hz -	PTk	5
30	I.S.-Frame-	14k -	0.75Hz		5
31	I.S.-Rope -	16k -	0.75Hz -	PTl	5
32	I.S.-Frame-	16k -	0.75Hz		5
33	I.S.-Rope -	18k -	0.75Hz -	PTm	5
34	I.S.-Frame-	18k -	0.75Hz		5
35	I.S.-Rope -	14k -	0.5Hz -	PTn	5
36	I.S.-Frame-	14k -	0.5Hz -		5
37	I.S.-Rope -	16k -	0.5Hz -	PTo	5
38	I.S.-Frame-	16k -	0.5Hz -	1 OF 2	5
39	I.S.-Frame-	16k -	0.5Hz -	2 OF 2	5

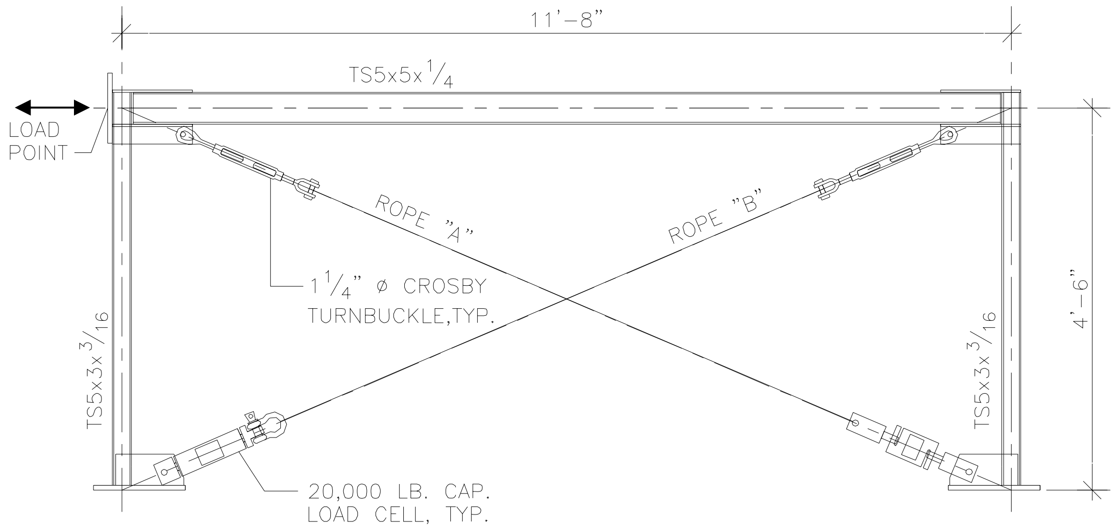


Figure 2. 9: 1:3-scale Test Specimen with Ropes

Figure 2. 10: Photograph of 1:3-Scale Test Specimen with Ropes

Tube steel sections were chosen for the columns and beam of the portal-frame specimen due to the inherent stability of closed sections, as well as the availability of tube steel sections with bending stiffness in the range of interest. The prototypical frame consisted of W14x120-A992 columns and W18x60-A992 beams. The model frame member sizes were initially chosen based primarily on similitude to the bending stiffness of the prototype members. This resulted initially in a HSS5x4x3/16-A500 being used for the beam, and a HSS5x5x1/4-A500 being used for each column. However, the column member size was reduced to HSS5x3x3/16-A500 after determining that the lateral load required to produce appreciable deflections in the original frame was beyond the capacity of the dynamic actuators available for the experiment. In addition, because a HSS5x4x3/16-A500 was not available, a HSS5x5x1/4-A500 was substituted for the beam.

2.3.3 TEST SPECIMENS WITH ROPES

The tests conducted with ropes utilized two 1-in.-diameter Amsteel-II ropes with typical eye-splices at each end, installed across the diagonal of the frame described in Section 2.3.2 (Figures 2.9 and 2.10). The ropes were identified with a simple notation indicating the location of the rope with letters *A* and *B*. The designation *A* indicates the rope that extends from the low side on the loaded end of the frame and the designation *B* indicates the opposite rope. The ropes were attached at the high end with 1.25-in.-diameter turnbuckles with a maximum length of 34.0 in. and an 8.0-in. available adjustment. The ropes were attached to 20,000-lb-capacity load cells, which were pin connected to the base of the frame columns at the low side of each rope.

2.3.4 LABORATORY SUPPORT FRAME

The tests were conducted in the Virginia Tech Structures and Materials Research Laboratory. The column base plates of the test-specimen portal frame were welded to the flange of a 22 ft 0 in.-long W14x193 beam, which was bolted to the laboratory reaction floor. The test specimens were loaded horizontally at a point 4 ft 6 in. above the W14x193 reaction beam with a 55,000-lb-capacity *MTS* dynamic actuator. The actuator was supported by a W12x53 lab column, which stood upright with its base bolted to the W14x193 beam and was braced in the direction of loading with a HSS5x5x1/4 brace (Figure 2.11).

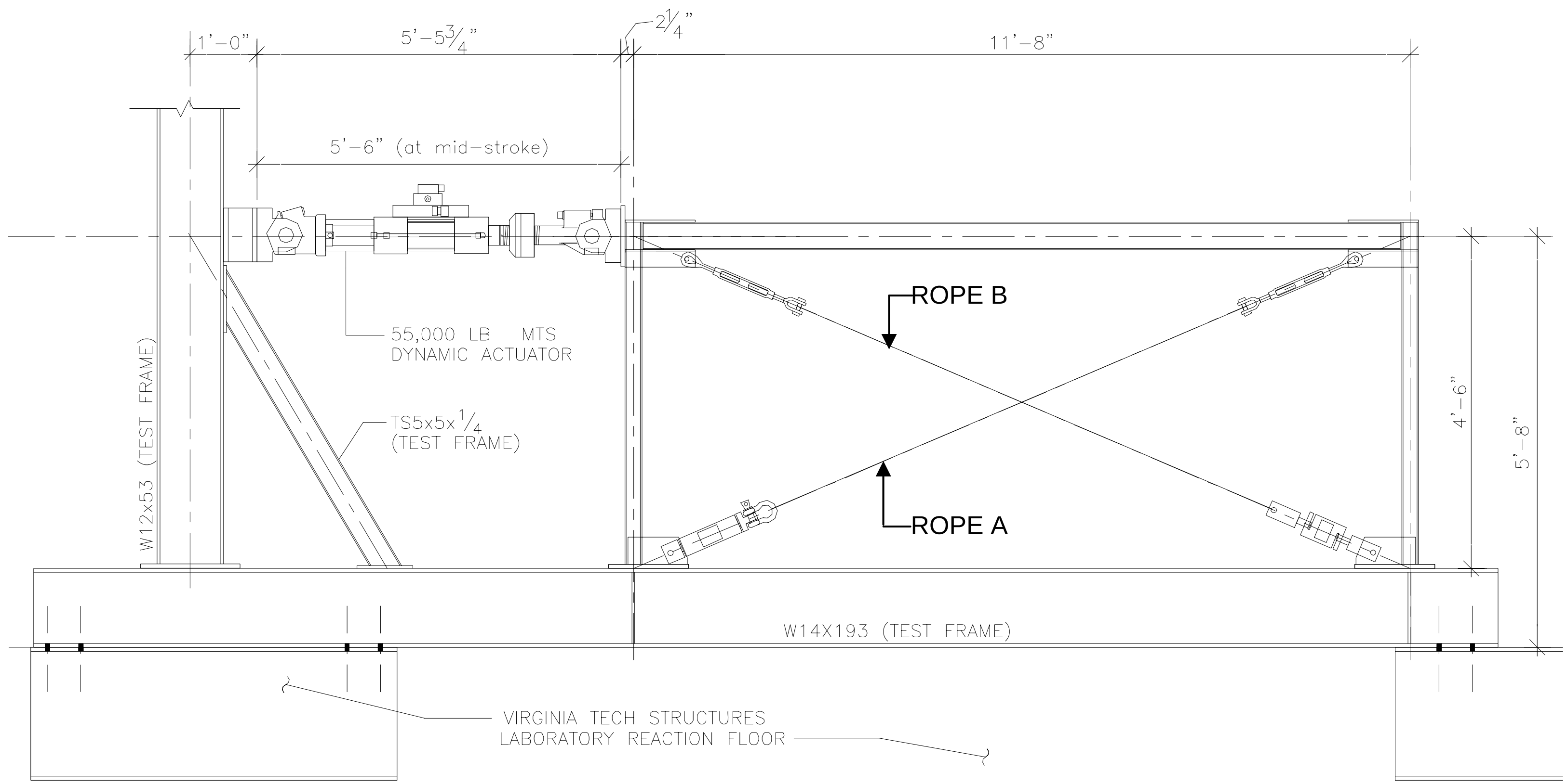


Figure 2. 11: 1:3-scale Test Setup

Support for the W12x53 was provided perpendicular to the plane of loading by bolting an 8 ft 0 in.-long C12x53 lateral support member between two additional W12x53 laboratory support columns, which were positioned 4 ft 0 in to each side of the main support column. These columns were also bolted to the laboratory reaction floor. To provide out-of-plane lateral support to the test specimen, 0.5-in.-diameter threaded rods were connected to the top of the test specimen beam at approximately 36 in. on center along its length (Figures 2.12 and 2.13). The threaded rods were connected to the test specimen such that movement in the direction of loading was allowed, while movement perpendicular to the direction of loading was restricted.

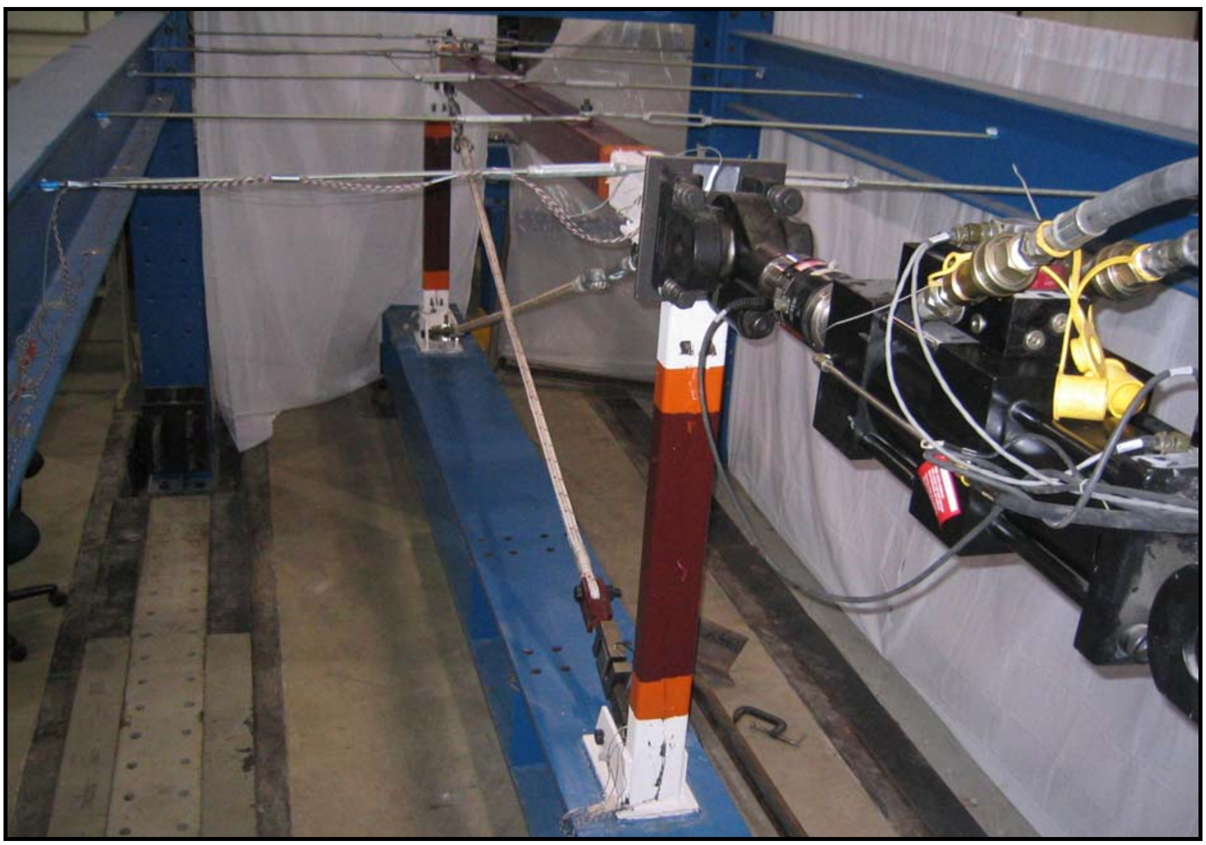


Figure 2. 12: Photograph of Lateral Bracing

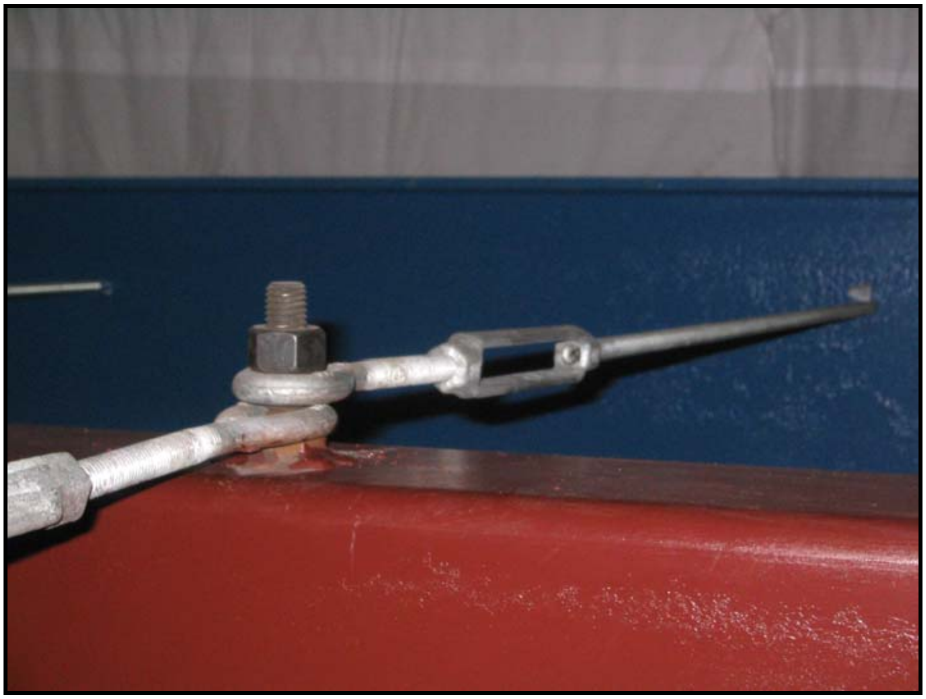


Figure 2. 13: Close-Up Photograph of Lateral Bracing

2.3.5 INSTRUMENTATION

Instrumentation was provided to measure the displacement and load at the load point, the strain near the base and near the top of each of the test-specimen columns, the strain at each end of the specimen beam, and the load in each rope (Figure 2.14).

As in the axial rope tests, the LVDT and load cell, internal to the MTS actuator, were used to measure load and displacement at the load point. Maximum bending strains of the columns and beam were monitored using 120-Ohm uni-axial strain gages on each side of each column, located 8 in. above the base of the frame and 8.75 in. from the centerline of the beam (Figure 2.15). Maximum bending strain of the specimen beam was monitored using two 120-Ohm uni-axial strain gages on the top and bottom of the beam, located 16 in. from the centerline of the columns. The load in each rope was measured using a 20,000-lb-capacity load cell (*Load Cell A* in Figure 2.14) and 50,000-lb-capacity load cell (*Load Cell B* in Figure 2.14), which were calibrated using the 300,000-lb-capacity Satec Universal testing machine. The load cells were calibrated from 0 lb to 20,000 lb.

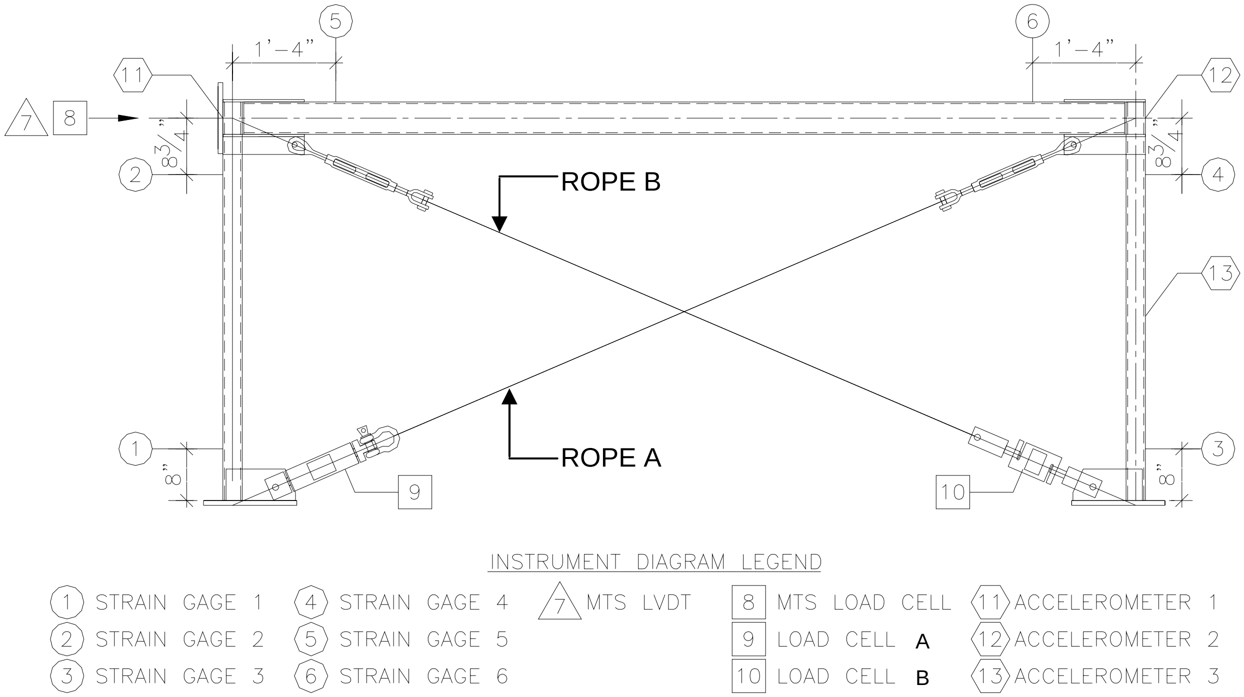


Figure 2. 14: Instrumentation Diagram

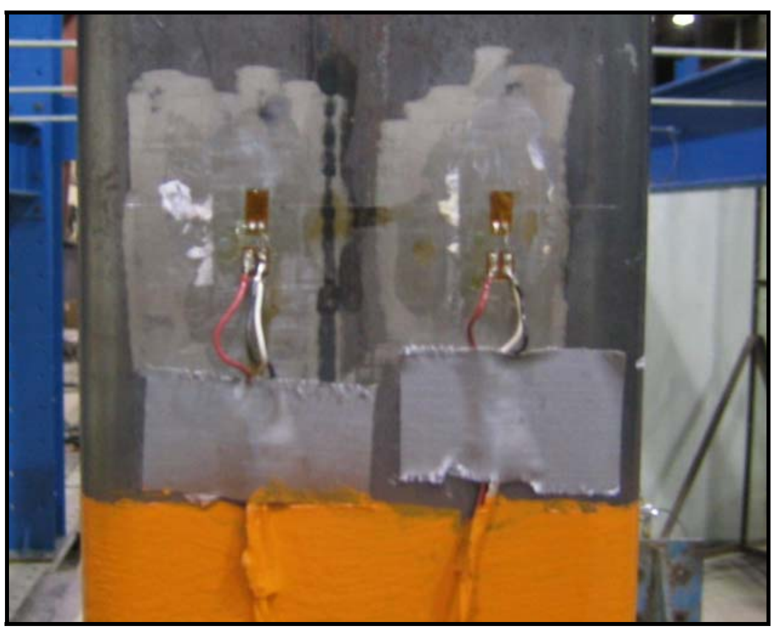


Figure 2. 15: Photograph of Typical Strain Gage Locations

The signals transmitted from all devices were converted in real-time and recorded directly by a Micromeasurements System 6000 data acquisition system. The optimum recording rate was determined to be 100 records per second, or one reading every 0.01 second.

2.3.6 MTS-LVDT DISPLACEMENT MEASUREMENT ADJUSTMENT

Displacement at the load point was measured using the internal MTS LVDT as described in Section 2.3.5. In the configuration used in this experiment, the MTS LVDT measured the relative change in distance between the support framing and the test frame, including the displacement of the test frame, the axial shortening or lengthening of the MTS actuator, and the movement of the laboratory support framing. The isolated displacement of the test frame was required for proper results. Therefore the combined response of the laboratory support frame and the actuator needed to be determined and subtracted from the total response measured by the MTS LVDT. To accomplish this, a wire potentiometer, referenced to the laboratory floor, was used to monitor the actual displacement of the frame during the initial static loading of the frame (Figure 2.16). Load versus total displacement measured by the LVDT and load versus actual load-point displacement measured by the wire potentiometer are plotted in Figure 2.17. The displacement measured by the wire potentiometer is termed "actual displacement".

A relationship between the elastic response of the laboratory support framing and the actuator was determined by calculating the average difference between the total system stiffness (measured using the MTS LVDT) and the true frame stiffness (derived from measured displacements determined using the wire potentiometer). By this method the cumulative elastic stiffness of the laboratory support frame and the actuator, termed support frame stiffness and abbreviated k_{SF}, was determined to be 5.63x10^{-6} in./lb. The wire potentiometer, which does not accurately measure dynamic displacements, was then removed. All subsequent displacement data measured using the MTS were adjusted as follows:

$$\Delta_{t_{ADJ}} = \Delta_t - \frac{F_t}{k_{SF}} \tag{2-2}$$

where Δ_t is the MTS LVDT-measured displacement at some point in time, t, F_t is the load measured at that same point in time, t, and $\Delta_{t_{ADJ}}$ is the adjusted MTS LVDT-measured displacement. The results applying this adjustment to the displacement data recording during the initial static load test are shown in Figure 2.18.

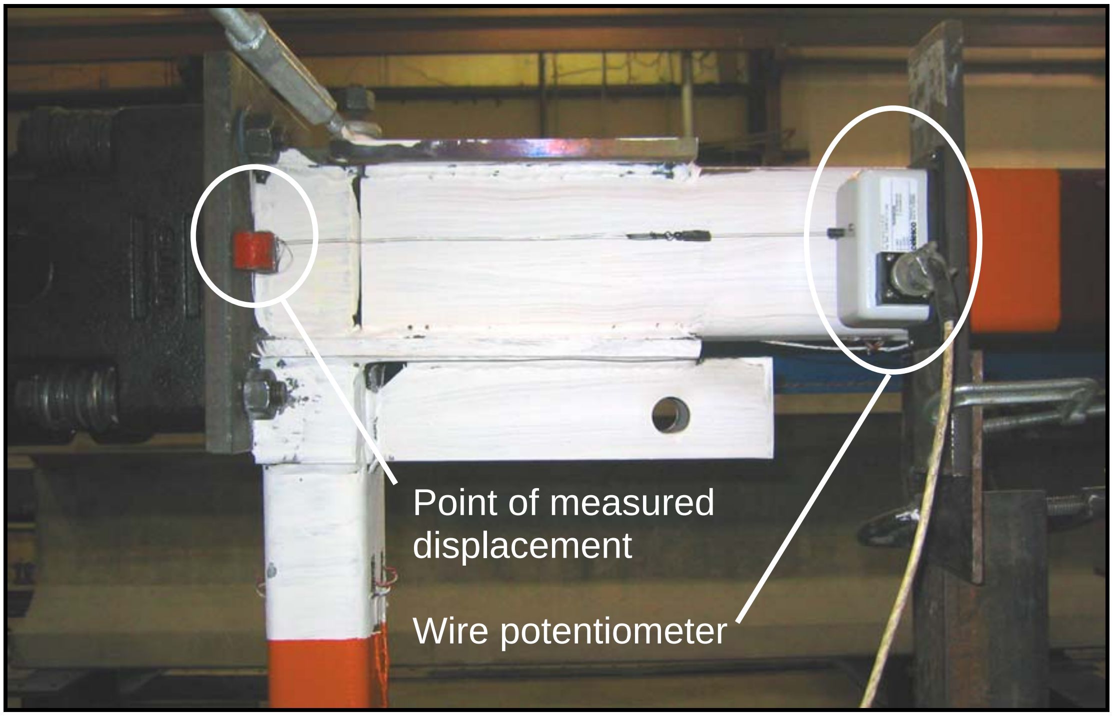


Figure 2. 16: Photograph of Actual Displacement Measurement during Static Loading

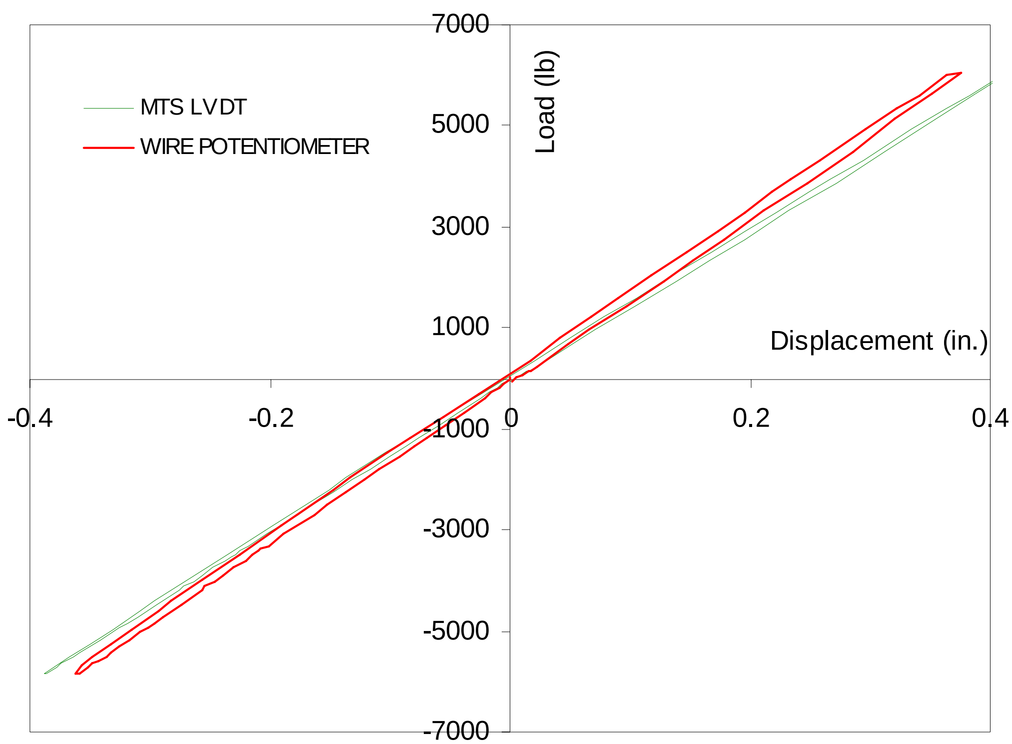


Figure 2. 17: Comparison of MTS Measured and Actual Displacement

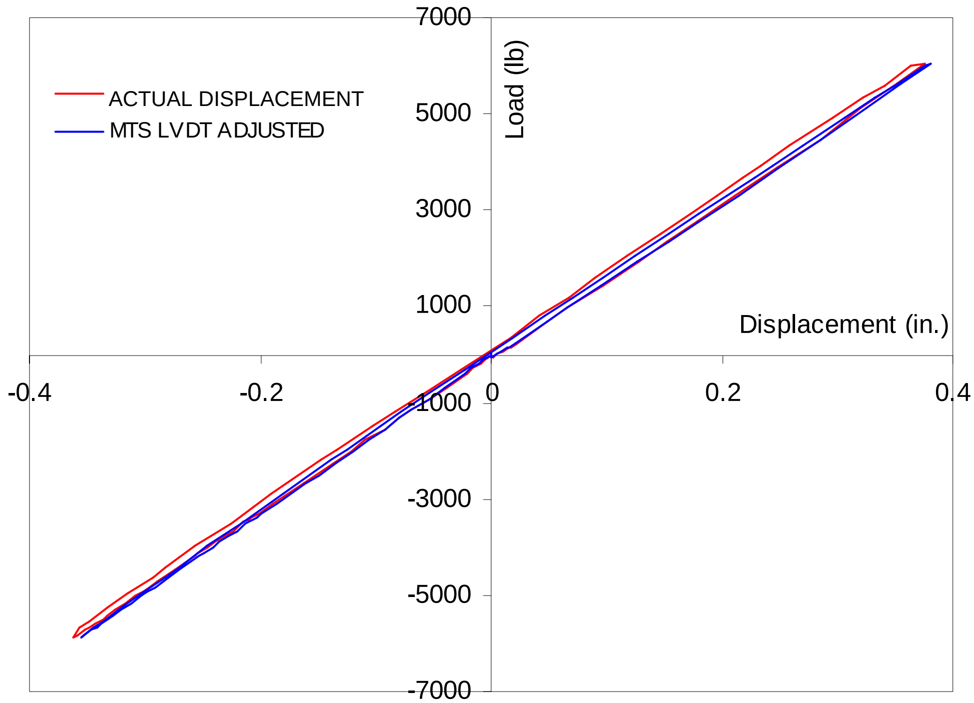


Figure 2. 18: Comparison of Adjusted MTS Measured and Actual Displacement

2.3.7 ROPE PRELOADING

Preloading the rope specimens during the axial load tests of the 0.5-in.-diameter ropes resulted in a fairly consistent response of the ropes in subsequent loading cycles in which the maximum load was less than the preload. The preloading also resulted in limited permanent deformation in subsequent loading cycles. It was therefore determined that preloading the 1-in.-diameter rope specimens prior to testing the rope specimens in the 1:3-scale moment frame was necessary to maintain effective stiffness in the ropes during multiple loading cycles. Based on anticipated elastic deformation capacity of the load frame and data from axial load tests from the manufacturer of the rope specimens, a preload equal to 25,000 lb was determined to be appropriate.

To apply preload to the ropes, the 55,000-lb MTS actuator was mounted horizontally at the base of a laboratory support column. The rope was attached to the actuator at one end, and attached to a dead-end reaction point at the other end (Figure 2.19).

The total available actuator stroke was less than the elongation of the ropes when subjected to the preload. Therefore, two cycles were required to apply the full preload. In the first cycle, the ropes were tensioned to approximately 20,000 lb. The preload apparatus was then adjusted to accommodate the elongated ropes. The ropes were then tensioned to a peak load equal to approximately 25,000 lb. One cycle of loading was completed as described.

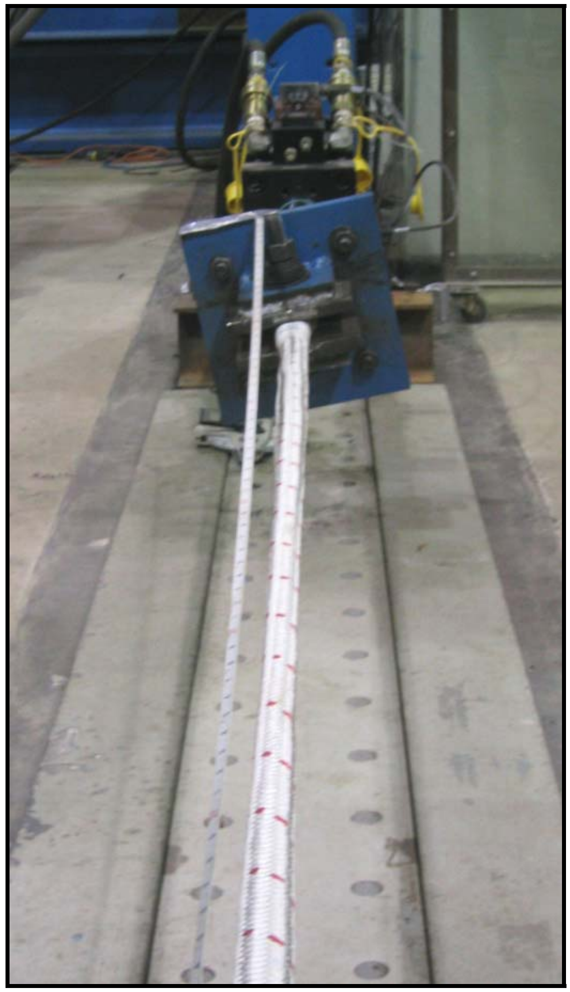


Figure 2. 19: Photograph of Rope Specimen Preloading

2.3.8 TEST DESCRIPTIONS

2.3.8.1 STATIC TESTS

Since only one steel frame was constructed, it was necessary for it to remain elastic until the final testing sequence. The purpose of the static test was to experimentally determine the elastic limit of the frame. All subsequent testing, prior to the final testing sequence, was then kept within that limit.

To determine the maximum elastic deflection experimentally, a quasi-static lateral load was applied to the frame without ropes, and load versus displacement was observed. The onset of first yield was noticed as the initial stiffness of the frame softened, which was marked by the decreased slope of the load versus displacement curve. The load was then reversed until a similar condition was observed in the opposite direction. The point of maximum elastic limit was determined to be 0.4 in. when the actuator reported a compression load of 6,500 lb. When the load was reversed to a displacement of 0.4 in., the tension load was 6,480 lb. It should be noted that the displacement reported in this section was the total deflection including the response of the support frame, without the adjustment described in Section 2.3.6.

The displacement recorded at the elastic limits (±0.4 in.) was used to program the experimental limit points of displacement using the MTS controller. The load recorded at the elastic limit was also used to define the maximum amplitude of sinusoidal loading in subsequent frame and rope tests.

2.3.8.2 FRAME TESTS

The frame was first tested dynamically without ropes to have a basis of comparison for the tests conducted with ropes. A load-controlled sinusoidal loading protocol was chosen for the dynamic frame tests. The form of the input was

$$F(t)_i = F_i \sin\omega_i t \tag{2-3}$$

In this function, $F(t)_i$ is the force applied at the load point in pounds, F_i is the amplitude of the sinusoidal loading in inches, ω_i is the frequency of oscillation in radians per second, t is time in seconds, and “i” represents a level of loading, incremented from 1 to 6 based on the incremental loading protocol presented in Table 2.4.

Table 2. 4: Amplitude and Frequency of Loading Function for Axial Rope Tests

Loading Function: $F(t)_i = F_i \sin\omega_i t$					
i	**F_i (lb)** *nominal*	**F_i (lb)** *actual*	**ω_i** (rad/sec.)	**Frequency** (Hz)	**Cycles**
1	3000	3117	π	0.5	10
2	3000	2994	$1.5\ \pi$	0.75	10
3	3000	2780	$2\ \pi$	1.0	10
4	6000	6304	π	0.5	10
5	6000	6013	$1.5\ \pi$	0.75	10
6	6000	5607	$2\ \pi$	1.0	10

Values for frequency were chosen to be 0.5 Hz, 0.75 Hz, and 1.0 Hz, and remained unchanged. Initially the values for amplitude of loading were chosen to be 6000 lb and 3000 lb based on the maximum elastic load of the frame determined during the static tests. It was learned during the initial dynamic tests of the frame that the peak amplitudes programmed were not reached precisely in load control. For lower-frequency loading of the frame tests, the peaks were overshot by approximately 6%. For higher-frequency loading, the programmed peaks were undershot by approximately 8%. It is noted that, flow rate capacities of the MTS system were checked, and were not being violated.

Additionally, the actual peak load values were being reached consistently. It was therefore determined that exact peak values in the range of interest could be reached by adjusting the peak load values, termed "span", using the MTS controller. To find the span that corresponds to target peak load, the specimen must be cycled at the desired frequency while the span was adjusted until the peaks being reached are equal to the target peak load. This process was required, in general, for all target peak loads and frequencies. In addition, the adjustment of the load-controlled loading protocol was dependent on the stiffness that was resisting the actuator. Because the stiffness of the steel frame was changed significantly when the ropes are added, programmed span values for each frequency of loading for the frame with ropes were different than the span values for the frame without the ropes. Therefore, if the target values for load amplitude were required to be 3000 lb and 6000 lb, the process of determining corresponding span values would have been conducted six times for the frame without ropes, and six times with the ropes prior to gathering any meaningful data.

The values for amplitude of loading were reconsidered, and it was decided that since the exact load values were chosen somewhat arbitrarily, adjusting them by ± 8% would be acceptable. It was also determined that subjecting the rope specimens to excessive load cycles, prior to the collection of useful data, was not in the best interest of the study, but subjecting the steel frame to multiple loading cycles would not be detrimental. The target amplitude of loading of the frame without the ropes was therefore set by the actual amplitude of peak loading reached during the dynamic tests with the ropes described in Section 2.3.6.3.

2.3.8.3 ROPE TESTS

Tests in which the steel frame was augmented with 1-in.-nominal-diameter Amsteel II ropes were conducted using the same incremental load-control loading protocol that was used to test the frame dynamically without the ropes.

Ropes were connected to the frame using 1.25-in.-diameter turnbuckles at the top and 20,000-lb-capacity load cells at the base of the frame. All channels of the data acquisition device were zeroed when the tension in each rope was equal to zero (Figure 2.20). The sag in the ropes was taken out by shortening the turnbuckles. A preload of 250 lb was sufficient to straighten the rope across the diagonal of the frame (Figure 2.21). The incremental loading protocol was followed (Table 2.4). Target values for amplitude of load are shown as F_i (nominal) in Table 2.4. The actual output amplitudes are shown as F_i (actual) in Table 2.4.

Figure 2. 20: Photograph of Specimen Condition at Zeroing of All Channels

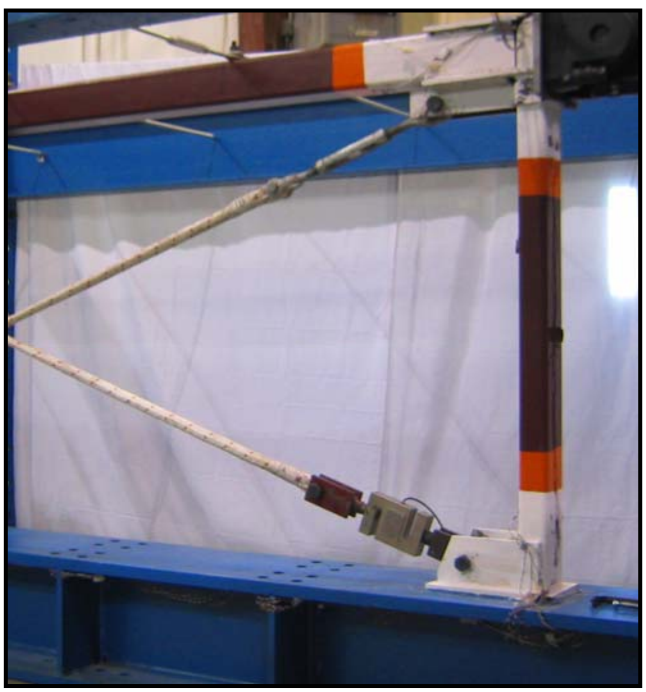


Figure 2. 21: Photograph of Taught Ropes

2.3.8.4 Rope Tests with 1,000-lb-Pretension

Upon concluding the incremental loading protocol, several additional tests with the ropes were conducted, where the initial tension forces in the ropes were increased from 250 lb to approximately 1000 lb. These tests are identified with the designation *PT* (pretension) and an alphabetical designation to distinguish each test. For these tests, the ropes were preloaded, and the system inputs were set to zero as described in Section 2.3.8.3.

2.3.8.5 Inelastic Frame Testing Sequence

The final test sequence consisted of alternating tests of the frame with ropes, and then without ropes. Each individual test consisted of loading the frame with five complete cycles of sinusoidal loading. The ropes were pretensioned to approximately 1,000 lb. All inelastic sequence tests are indicated with the designation "I.S." and listed in Table 2.3.

The first test of the sequence was conducted on the frame with ropes installed. A sinusoidal load was applied with amplitude of 8,500 lb and frequency of 0.75 Hz. The ropes were then removed, and the sinusoidal load was repeated. Ropes were then re-installed and sinusoidal loading was applied with amplitude of 10,000 lb and frequency of 0.75 Hz. Again the ropes were removed and the loading repeated. The loading amplitude and frequency were adjusted, and the ropes were installed and removed repeatedly, as indicated in Table 2.3 in the order in which they were conducted.

It should be noted that the values designating the sinusoidal loading amplitude in Table 2.3 (Amp.) are nominal and indicate the values programmed into the MTS controller, not the actual values of load amplitude observed. In fact, as the tests progressed, it became obvious that the flow rate limit of the MTS system had been reached. Therefore, to achieve higher loads, the frequency of loading was reduced to 0.5 Hz for the last two tests.

2.3.9 1:3-Scale Frame Test Results

The 1:3-scale frame test was conducted to observe the response modification of a steel moment frame augmented with Amsteel II rope devices, quantify the amount of energy dissipated by the devices, provide a basis of comparison for a finite element model, and observe the effect of pre-load in the rope. Results indicate that the rope devices can significantly reduce drift, provide some energy dissipation, and remain effective through several loading cycles. Additionally, the rope devices were observed to be more effective in limiting drift and dissipation energy with an initial pretension.

Tests conducted with amplitude of 6,000 lb and loading frequency of 1.0 Hz were chosen to illustrate the preliminary findings. Figure 2.22 shows a comparison of the total response of the frame based on the deflection at the load point versus the input loading. In Test 8 the steel frame without ropes was loaded through 10 cycles. It was observed to have the greatest overall drift, 0.37 in., representing 0.68% of the frame height, with an extremely small amount of hysteretic behavior, as was expected. In Test 14, the load in the ropes prior to testing was 200 lb and the overall drift of the frame was reduced to 0.31 in., representing 0.57% of the frame height, with limited hysteretic behavior observed. In Test 16, pre-tension of 1000 lb was applied to the ropes. The total drift was reduced to 0.19 in., representing 0.35% of the frame height, with stable hysteretic behavior observed throughout five cycles of loading.

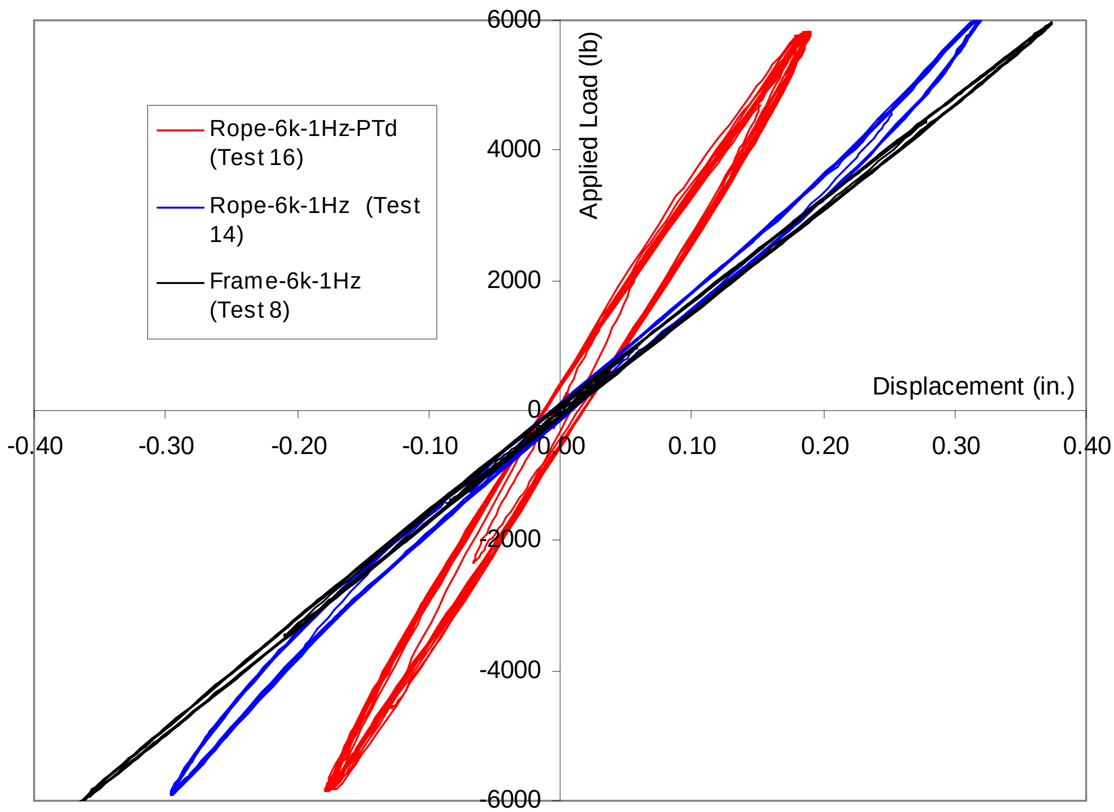


Figure 2. 22: Comparison of Displacement at the Load Point vs. Applied Load

Rope force comparisons for each rope of Test 14 and Test 16 are shown in Figures 2.23 and 2.24. A marked increase in energy dissipation was observed for Test 16, in which a 1000-lb preload was applied to the ropes, when compared to Test 14. Additionally, in contrast to the ropes from Test 14, the rope response of Test 16 indicated hysteresis by the ropes as negative displacement of the frame, relative to the direction of tension loading in the ropes. This was the result of the preload in the ropes being relieved. It was also observed that some tension equal to approximately 100 lb remained in all ropes throughout loading, due to the weight of the load cell.

In subsequent studies, conducted as a part of this experimental program, pre-tensioned ropes were shown to have an adverse effect on the dynamic response of steel moment frames. Essentially, pre-tensioned ropes were determined to act as force attractor during a seismic ground motion, effectively decreasing the fundamental period of a structure.

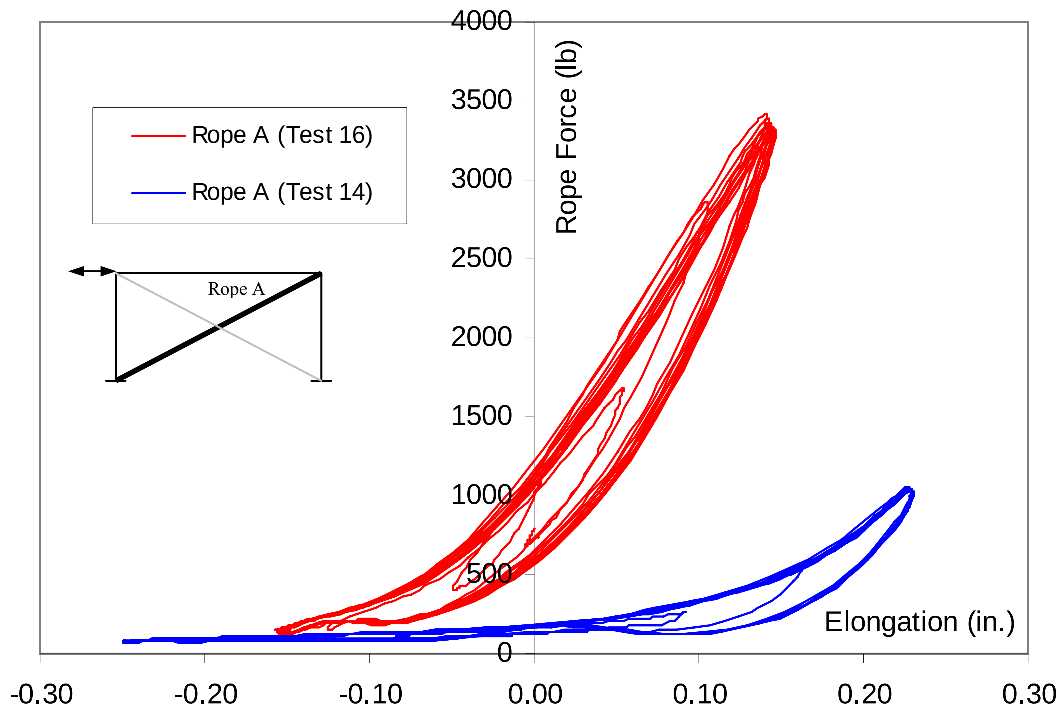


Figure 2. 23: Comparison of Rope A Force versus Elongation of Ropes

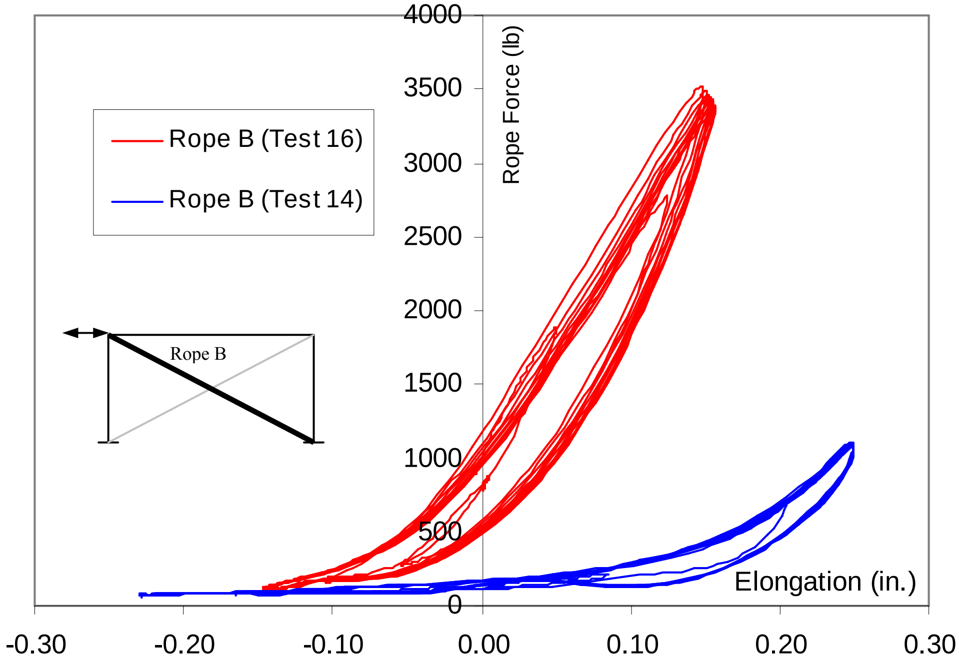


Figure 2. 24: Comparison of Rope B Force versus Elongation of Ropes

2.4 Minimum Specified Strength Tests

2.4.1 Overview

Quasi-static axial load tests were conducted using 1-in.-nominal-diameter Amsteel II rope. The tests were conducted to determine the response of the ropes up to the average break strength (ABS) published by the rope manufacturer. It was of interest (1) to verify that the rope capacity was consistent with published manufacturer data, and (2) to determine if the response is repeatable without excessive permanent deformation occurring in the rope throughout multiple cycles approaching the ABS of the rope. Rope specimens used for the quasi-static tests were the same ropes that were used in the 1:3-scale frame tests. Rope test designations are provide in Table 2.5.

Table 2. 5: Rope Test Designations

Test Designation	Rope Type	ABS (kips)	Rope Length (ft)
B1	1-in. diameter, Amsteel II	55	8
B2	1-in. diameter, Amsteel II	55	8

2.4.2 TESTING FRAME

The setup used for the quasi-static rope tests was composed of two steel support fixtures placed approximately 18 ft apart and bolted to the reaction floor. A 60,000-lb-capacity hydraulic actuator was attached to one support using a 1-in.-diameter pin (Figure 2.25). A 55,000-lb load cell was installed in series between the actuator and the cable specimens (Figure 2.26). The cable specimens were connected to the dead-end support using a 3/4-in.-diameter bolt.

Hot-rolled steel members, 24 in. deep by 8 ft long were placed approximately 2 ft to each side of the cable along the full length of the experiment. OSB sheathing was clamped to the top of the beams (Figure 2.26). The beams and OSB sheathing were used to provide protection against whipping of the ropes upon rupture.

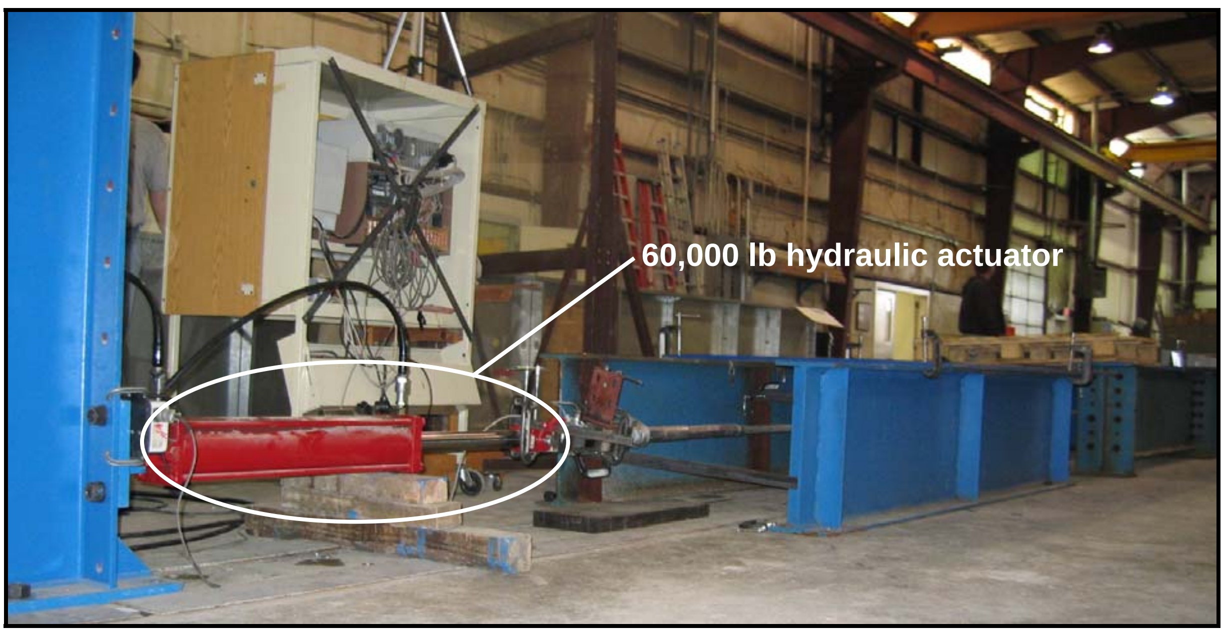
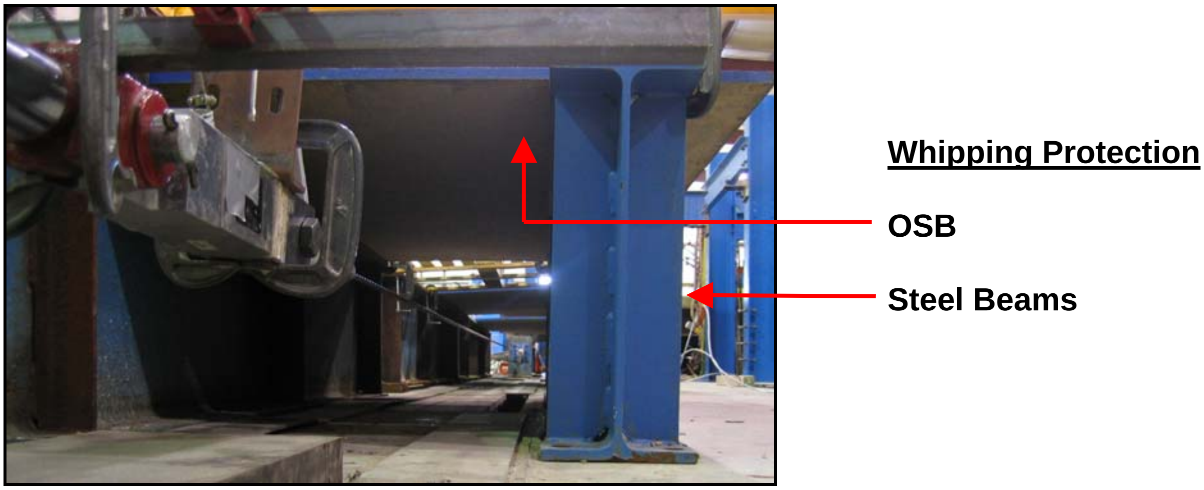


Figure 2. 25: Photograph of Testing Apparatus from Loading End



Note: Actual rope test not illustrated. However, rope test apparatus was identical.

Figure 2. 26: Photograph of Cable Test from Loading End

2.4.3 Instrumentation

To procure the desired ultimate load and load-versus-end-displacement relationship of the cable, displacement and load were measured and recorded continuously. A 55,000-lb-capacity load cell was used to measure load. A spring-loaded, wire-type potentiometer with 40 in. of available travel was used to measure end displacement of the cable. Figure 2.27 depicts the arrangement of these devices. The electronic signals transmitted from both devices were converted in real-time and recorded using a Micromeasurements System 5000 data acquisition machine.

The load cell and wire potentiometer were calibrated to ensure that accurate data would be recorded. The load cell was calibrated directly using the Satec universal-type testing machine at the Virginia Tech Structures and Materials Research Laboratory. Figures 2.28 and 2.29 show the Satec calibration data and the load-cell calibration data, respectively. The wire-type potentiometer was calibrated using a dial-type stand extensometer.

2.4.4 Loading Protocol

A load-controlled loading protocol based on the average break strength (ABS) of the cables was used. The ropes were initially conditioned by applying load to the ABS published by the rope manufacturer, to minimize permanent deformation in subsequent loading cycles. Subsequently, each specimen was cycled two times between 0 lb and 55,000 lb.

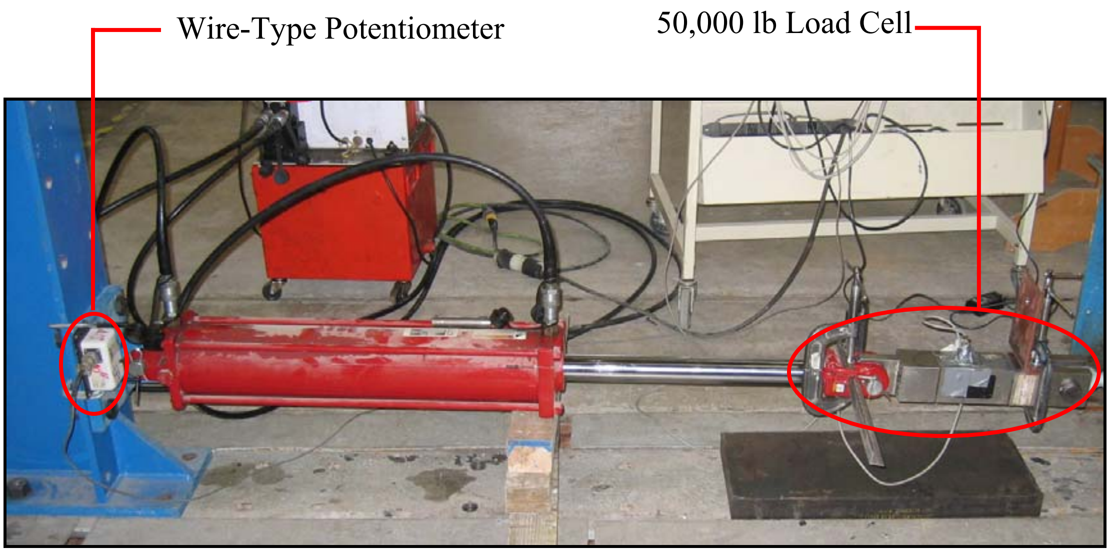


Figure 2. 27: Photograph of Instrumentation at Loading End

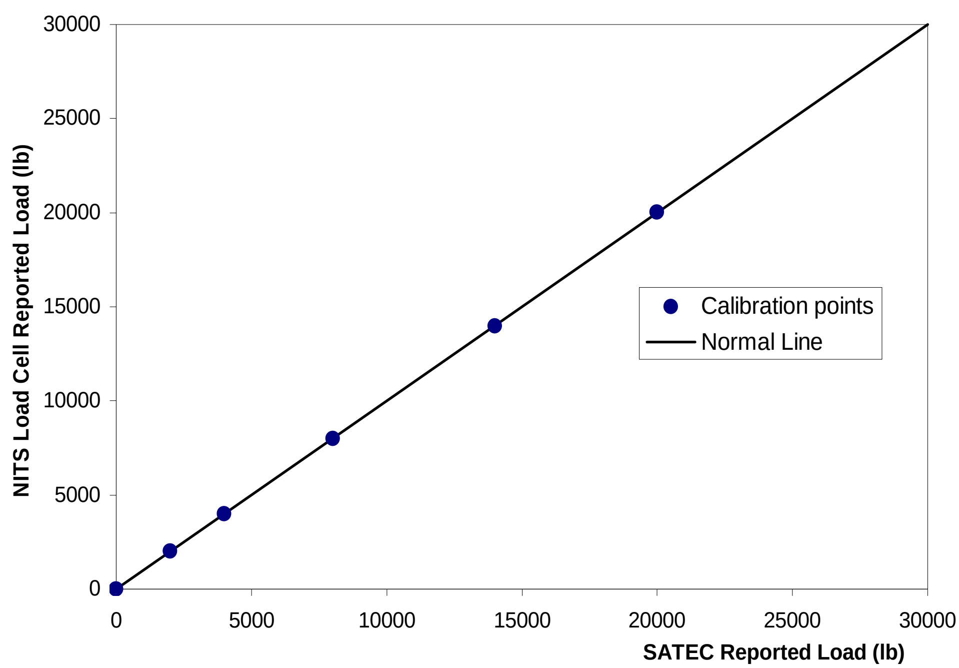


Figure 2. 28: SATEC Calibration Data

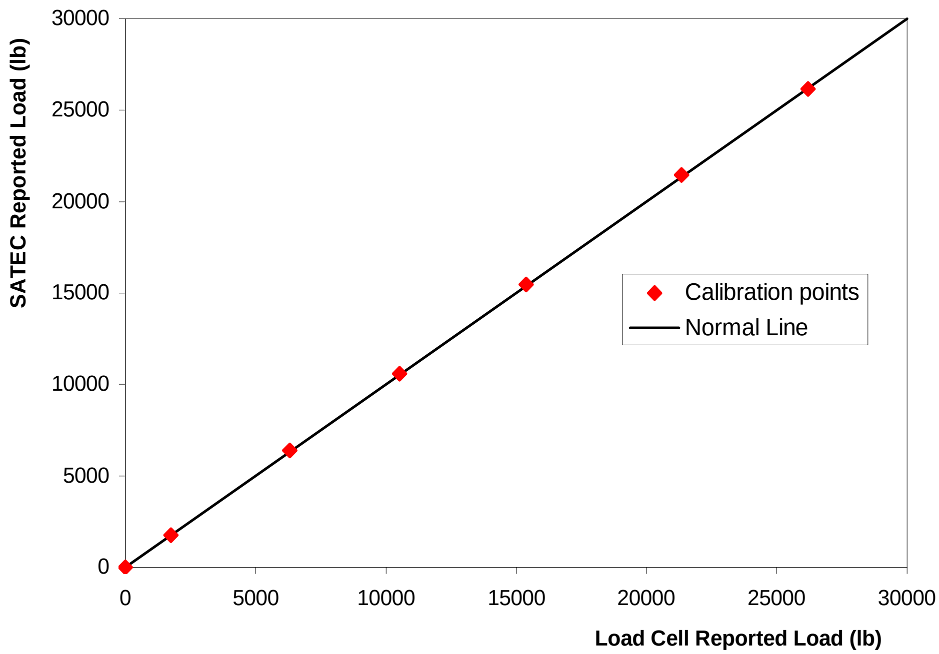


Figure 2. 29: 50,000 lb Load Cell Calibration Data

2.4.5 RESULTS

Test results are illustrated in Figures 2.30 and 2.31. In Figure 2.30 the load versus displacement response during the initial conditioning of each rope specimen is shown. Both rope specimens exhibited nearly identical stiffness throughout loading. The jagged appearance of the response curves is a result of the quasi-static loading, during which load is held for a short period of time, allowing the rope to relax slightly. In Figure 2.31 the load versus displacement response during two subsequent loading cycles is shown for each rope specimen. Similarly to the initial loading curves in Figure 6, the response curves are nearly identical. Unlike the response observed during the initial conditioning of the ropes, the rope responses in the loading cycles subsequent to the conditioning curve gain stiffness at much lower elongation levels, and do not lose stiffness at the upper level of loading.

It was determined that the response of the ropes could be repeated over multiple cycles at loads approaching the rated capacity of the ropes with minimum permanent deformation. It should also be noted that neither rope specimen was broken during these tests.

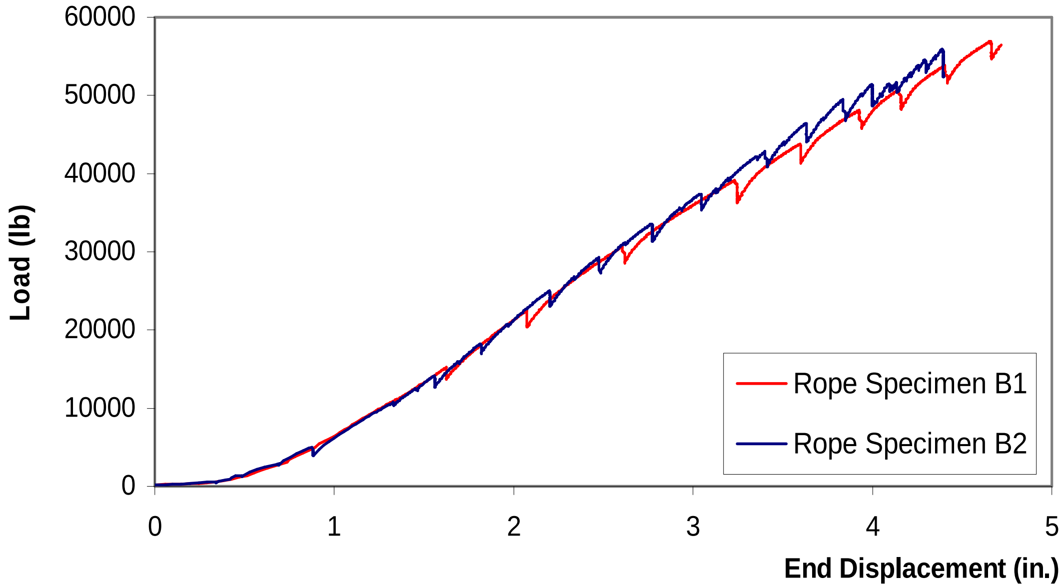


Figure 2. 30: Load vs. End Displacement: Initial Conditioning to RBS

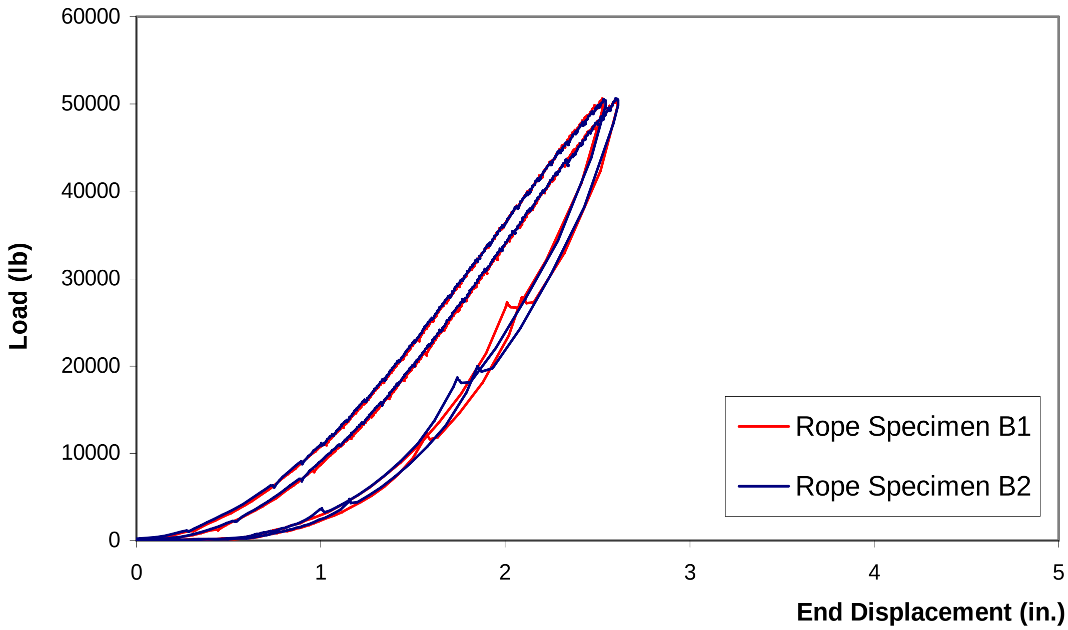


Figure 2. 31: Load vs. End Displacement: Post-Conditioning Cycles