CHAPTER 6

Conclusions and Recommendations for Continued Research

6.1 INTRODUCTION

The purpose of this study was to evaluate the use of synthetic fiber ropes for augmenting steel moment frames to mitigating damage caused by earthquake-induced ground motions, thereby improving the structural performance. The type of rope chosen for the study was Amsteel II, a double-braided rope produced by Samson Rope Company. Specific objectives of the study were as follows:

- Determine the point-to-point component behavior of the ropes and model that behavior in a finite element program.
- Design a method for connecting the rope devices to a moment frame to include a means by which the initial conditions of the ropes could be adjusted.
- Determine whether initial pretension or an initial slackness in the rope provides a more desirable response.
- Conduct nonlinear response history analyses, incorporating elements representing rope response, to optimize the rope configuration, defined as the initial slackness in the rope and the cross-sectional area of the rope, for improving the performance of a two-story prototype structure.
- Develop a scaled steel moment frame model for shaking-table testing, based on the prototype frame and optimized rope definitions.
- Test the viability of the rope device as an effective means of mitigating total and residual floor and roof drift, while limiting the increase of base shear to an acceptable level, through a 1:6-scale shaking table experiment.

The present chapter briefly summarizes the research conducted for this study, including pertinent conclusions from each chapter, and provides recommendations for future research in this field.

6.2 INITIAL EXPERIMENTAL ROPE STUDIES

To obtain an understanding of the dynamic and static response characteristics of the ropes, three experiments were conducted. A series of dynamic axial rope tests was conducted to determine the response of the ropes, previously used in drop tests, when cycled through displacements and velocities representative of those likely to be experienced by structural elements during a seismic event. A series of tests using a 1:3-scale steel moment frame with and without rope devices was conducted to determine the suitability of ropes for structural application. Static tests of ropes used during the 1:3-scale dynamic testing were conducted to determine rope response when subjected to repeated quasi-static load cycles approaching the minimum break strength of the ropes. Notable findings from each series of tests are as follows:

Dynamic Axial Rope Tests:

- Rope response was repeatable through multiple loading cycles, provided the maximum load previously experienced by the rope was not exceeded. For loading cycles in which the maximum load previously experienced by a rope specimen was exceeded, permanent deformations were observed to occur. The extent of the permanent deformation was dependent on the magnitude of load above the previously experienced load level. It was determined that permanent deformations occurring as described would result in the loss of effectiveness of the ropes after the first large drift excursion of a structure. Therefore, conditioning of the ropes, defined as loading the rope above the anticipated rope force, prior to installation into a structural system was determined to be a suitable method for eliminating excessive permanent deformations, and would result in repeatable rope response for the intended application.
- Conditioned ropes demonstrated a repeatable response, with consistent loading and unloading responses through multiple load cycles.
- A smooth, increasing stiffness of the loading curve was observed
- The response of the ropes was not velocity-dependent within the range of velocities corresponding to velocities experienced in low to mid-rise structures during seismic events.

1:3-Scale Frame Tests:

- An effective method of installing ropes using techniques commonly available in current construction was developed.
- The magnitude of damping in the ropes increased as the elongation of the ropes increased.
- A 1-in.-nominal diameter rope provided significant reduction in frame drift.
- Response of the ropes was observed to be repeatable through several loading cycles, and minimal permanent elongation was observed throughout testing.

Static Axial Rope Tests:

- The rope response was repeatable through multiple load cycles between zero load and minimum rope break strength.
- The repeatable loading curve obtained during the static axial rope tests provided a basis for the definition of the rope element used in analytical modeling of the prototype structure in Chapter 4.

6.3 DEVELOPMENT OF 1:6-SCALE SHAKING TABLE MODEL

Initial experimental rope test results were incorporated into a nonlinear finite element models for modal analyses, push-over analyses, and response history simulations for the purpose of determining the optimum rope configuration in a prototypical 2-story moment frame structure, and to develop a 1:6-scale shaking model for shaking-table testing. Ropes were modeled based on the nonlinear loading curve of ropes developed from static rope tests using a tri-linear, elastic, tension-only element. The moment frame was modeled based on nominal steel properties. Based on the prototype structure and the optimum rope condition developed, a 1:6-scale steel moment frame was designed for a shaking table experiment in which two moment frame specimens were excited with Northridge ground motions. Notable findings from the analytical development of the 1:6-scale frame are as follows:

- From a parametric study using the analytical models, it was determined that the optimum rope condition for the prototype frame consisted of three times the cross-sectional area of ropes tested in the static axial rope tests with a 0.4-in. initial-slackness gap.

- With the optimum rope condition incorporated into the model, a significant reduction to maximum and residual floor and roof drift was estimated using response-history analyses with a suite of six ground-motion records, scaled per building-code provisions. A corresponding increase in base shear was estimated to be less than 30% for all groundmotions. The parametric study results provided validation for further development of the concept of using rope devices for the stated purpose.
- Proper scaling of the prototype frame and rope response was verified using modal analyses, push-over analyses, and response history simulations.

6.4 STATIC AND MODAL TESTING OF THE 1:6-SCALE MODEL

Static and modal testing of the 1:6-scale experimental model was conducted to ensure that the fabricated model was similar to the analytical model on which its design was based. These tests were also conducted to verify that the static and dynamic response characteristics of the frames tested with and without the rope devices were sufficiently similar for the evaluation of the modification to the frame response with rope devices added. Static tests, impact hammer tests, and sinusoidal base-input tests were conducted on both frames. Notable findings of the static and modal testing are as follows:

- Significant damping and stiffness contribution by the leaner frame was observed. This was considered to be acceptable since the leaner frame would contribute the same amount of stiffness and damping to each frame tested. Therefore, the evaluation of the modification of frame response due to the addition of rope devices was determined to be valid.
- The static and dynamic response characteristics of the frames were considered to be sufficiently similar for comparisons made between frames tested with and without ropes subjected to Northridge ground-motion input.

6.5 ANALYSIS AND EXPERIMENTS FOR THE 1:6-SCALE SHAKING TABLE TESTS

A series of 1:6-scale shaking table experiments was used to test the improvement to the performance levels of the 1:6-scale steel moment frame, representing moment frames of a prototype two-story office structure with ropes added. Simulations of the 1:6-scale frame were conducted to predict the displacements, accelerations, base shear, and residual drift of the frame during testing, and to establish magnitudes for Northridge ground-motion input that would result in two distinct performances of the moment frame during testing. A 30% Northridge ground-motion input was used to observe the modification to the frame response, with the addition of rope devices, at amplitudes of displacement corresponding to service-level displacement amplitudes. A 180% Northridge ground-motion input was used to observe the modification to the frame response, with the addition of ropes, at amplitudes of displacement in which significant yielding of the frame occurred. Experimental and analytical results were compared to determine the accuracy of the analytical model. Experimental data from tests conducted with and without ropes was compared to evaluate the modification to the performance of the 1:6-scale frame when ropes were added. Notable finding of the analytical and experimental studies are as follows:

Evaluation of the Analytical Model

- Excellent correlation was observed between the analytical analyses and the experimental results for the 30% ground-motion tests with respect to displacement, acceleration, and base shear. Maximum and minimum values observed were also predicted with good accuracy, and the predicted shape of the corresponding traces of these values in time was adequate.
- The analytical model was found to be an excellent tool for establishing desired performance levels of the frame for the 30% and 180% ground-motion tests.
- For 180% ground-motion tests, the analytical model provided very accurate predictions of residual drift, reasonably accurate predictions of maximum and minimum acceleration and base shear, and inaccurate predictions of maximum rope force.
- Maximum rope force values observed in the experiment were significantly overestimated in the analytical model. This was attributed to the tri-linear elastic response definition for the element used to model the ropes, which does not model the reduced stiffness of the unloading response of the ropes.
- Overall, the analytical model was adequate in predicting the response of the 1:6-scale model for the shaking table experiments. In general, the inaccuracies of the analytical model resulted in conservative estimates of response parameters.

Experimental Results

- Response of low-amplitude motion, consistent with service wind loading or small-scale ground motion, was not affected by the ropes.
- The initial rope condition necessary to provide intended response modification to a frame subjected to large-scale ground motion was not affected by low-amplitude motion of the frame.
- The 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.
- The 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 floor 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 floor 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 repeatable response characteristics throughout the testing.
- Performance of the 1:6-scale frame was significantly improved by the addition of the rope devices.

6.6 RECOMMENDATIONS FOR CONTINUED RESEARCH

Recommendations for future research are included herein and address further investigation required of the ropes for use in structural applications, possible improvements to the analytical model, and improved methods for conducting shaking-table tests.

Synthetic Fiber Ropes

- Improvements to the method used for connecting ropes to steel frames by which load cells would not be required to install ropes, such as low-tech calibrated tension indication devices installed in series with the ropes, should be investigated.
- After experiencing an extremely large ground-motion event, ropes could possibly act as a stabilizing element in a structure that has experienced significant residual drift, subjecting the rope to constant tension. If ropes are intended to provide stability as described, the

phenomenon of load-shedding by the ropes subjected to constant tension needs to be investigated.

- Synthetic fibers, such as the fibers used to construct Amsteel II rope, are susceptible to damage at lower temperatures than more commonly used building products, such as steel, concrete, and masonry. Because the risk of fires increases after a large seismic event, the investigation of methods of fire protection for rope devices is required prior to their use in structural applications.
- The core of Amsteel-II ropes is the primary source of the response aspects of the rope. The actual diameter of the core is significantly smaller than the nominal dimension due to a thick, nylon sheathing used to protect the core. In a structural application, the protective sheathing is not required for structural considerations. A rope constructed of core material only would result in a reduction to the cost of the ropes and should be investigated.

Analytical Model

- Improvement to the analytical model could be made by refining the method used to model the rope device. Specifically, determining a method for defining the unloading portion of the response curve, which changes depending on the amplitude of rope stretching, would be useful.
- Additional improvement to the analytical model could be made by defining nonlinear damping of the steel frame.
- Analyses of taller structures with refined rope definitions would be useful in determining the limit of applicability of the rope devices.

Shaking-Table Testing

- Improvements to data collection of shaking table tests could be made by employing a method for measuring displacement of the diaphragm levels that does not rely on accelerometer data, particularly for testing in which the frame response is inelastic