Chapter 1

Introduction and Literature Review

1.1 Introduction

Ground motion due to earthquakes can cause significant damage to buildings and in some cases cause the complete failure of structural systems. While some areas of the world experience much more violent and frequent earthquakes than others, they can occur anywhere and at any time. There are methods to reduce the effects of ground motion such as tuned mass dampers, base isolators, and other types of active and semi-active control systems, but these devices can be very expensive and are not practical for most buildings. As a result, when a major earthquake strikes in an area that doesn't frequently experience them or in an area that because of economic reasons cannot afford such devices, the effects can be devastating. It is because of this and other factors that there is an interest in designing passive control devices that can effectively mitigate the forces caused by an earthquake at a fraction of the cost of other damping systems.

The long-range goal of this multiple-stage research project is to eventually use synthetic fiber ropes as passive earthquake dampers (known as Snapping-Cable Energy Dissipators, or SCEDs) by mounting them in a slightly slack configuration diagonally across vertical bays in a structural frame. When a seismic event occurs, the energy that is created by the ground motion is transferred to the building and causes the frame to sway back and forth. This will cause the ropes to transfer from the slack (loose) state to a taut (tight) state and dissipate some of that energy. This transition causes the rope to "snap," and the tension in the rope that builds up during the taut phase is known as the snap load. The ropes will also act as restraints to limit the relative displacement (drift) of the bay between the two ends.

The purpose of this research is to continue and expand upon the work that was started by Nicholas Pearson in his research, "Experimental Snap Loading of Synthetic Fiber Ropes." In those experiments, ropes with different material properties, lengths, and diameters were tested under both static and dynamic loads. The experimental data that was collected in the initial research was organized and analyzed as a part of this research to evaluate the behavior of the ropes during the snapping action. Additional tests were also conducted for this project under more controlled conditions to better understand how the ropes change throughout a sequence of similar snap loadings and also to determine the amount of energy that is dissipated. The data from both projects was then used as input parameters for a mathematical model that was developed to characterize the behavior of the ropes during a snap load. This model will be utilized in subsequent research involving the finite element analysis of the seismic response of structural frames containing SCEDs.

1.2 Literature Review

1.2.1 Snap Loads

A snap load is produced when a rope transfers from a slack (loose) condition to a taut (tight) condition in a very short period of time. This snap load is a tensile force that is nearly instantaneous and can be several orders of magnitude larger than the normal static or dynamic loads that are experienced (Plaut et al. 2000). When a rope is alternately slack and taut during the motion of a structure, snap loads tend to occur. When a rope becomes taut, the internal forces increase sharply to a high value and then decrease sharply as the rope becomes slack again. The ropes in this study were able to withstand the forces that are produced by the snap loads, but the fibers were pulled tightly together and the ropes suffered some permanent deformation (Pearson 2002).

Plaut et al. (2000) investigated the effects of snap loads on moored buoys and floating breakwaters that were held in place by a series of cables that were attached to the sea floor. When a cable was stretched to or beyond its natural length, a snap load occurred. At the end of the snap load, the cable rebounded and became slack again. While slack, the cable has no axial or bending stiffness and, therefore, cannot carry a compressive load.

Niedzwecki et al. (1991) considered the dynamic response of marine cables under regular sea conditions. Their model simulated a deep ocean drilling assembly that was suspended from a large ship by a deepwater marine cable system. It was discovered that depending on the rate of tensioning, the cables can experience severe snap loads that are nonlinear in nature for time domain simulations. The snap loads can also cause fatigue of the cables and reduce their useful life.

Abrate et al. (2003) studied the nonlinear dynamic behavior of parachute static lines for use during military airborne operations. These fabric structures are attached at one end to an airplane and to the ripcord of a soldier's parachute at the other. When this line becomes taut, a snap load occurs and the parachute is deployed. These static lines were tested under dynamic conditions by attaching weights to one end and dropping them from various heights. The static lines exhibited a highly nonlinear force-strain history and experienced large deformations. The force-strain history varied based on the amount of mass, the drop height, and the length of the line. A mathematical model for predicting the dynamic response of the static lines was created by using the acquired force-strain histories. This expression produces a theoretical force value and is dependent on several coefficients and the strain to which the static line is subjected. Results also indicated that a significant amount of energy was dissipated during the snap loads. The static lines absorbed a portion of the kinetic energy that was built up by the falling weights. The energy absorbed per unit length of the line was quantified by calculating the area beneath the force-displacement curve.

1.2.2 Energy Loss and Damping Properties

The synthetic ropes that were used in this research and the preceding research all consisted of high modulus fibers that exhibited good elastic properties and very high ultimate strengths. When loaded, the fibers are able to stretch well beyond their natural length without rupturing and nearly return to their original length. The ropes are made up of thousands of individual fibers that are wound into yarns. These yarns are then twisted into plied yarns, which are then compiled into rope yarns, which are then assembled into strands, which are then braided into ropes (Pearson 2002). There is no physical bond that holds the individual components of the rope together, so when the rope stretches, the strands are able to move somewhat independently of each other. Therefore, when a tensile load is applied to the ropes, there is both a lengthening of the fibers and a rotation of the strands. Both of these occurrences cause the components of the rope to slide against each other, creating the friction that dissipates the energy of the snap load.

Raoof et al. (1993, 1994) considered the extensional-torsional behavior and response of wire ropes under impact loading. Due to the helical geometry of the strands, a tensile load produced a twisting action in addition to the extension of the cable. However, because of the material properties of the steel and the configuration in which the strands are wound together, steel cables cannot produce the same amount of friction due to slippage as a rope and therefore, cannot dissipate as much energy.

Huang et al. (1996 a,b) looked at the extension of cables in the presence of dry friction and the frictional losses in axially loaded cables. It was shown that dry friction is the main cause of damping in cables and that this occurs due to the twisting and bending of the individual wires. Explicit load-elongation relationships were obtained from the loading, unloading, and reloading of the cables which produced hysteretic loops that characterize the structural losses of the cable.

Wu et al. (2003) investigated the effect of cable loosening on the seismic response of prestressed concrete cable-stayed bridges. A 3-D model was used to conduct a dynamic analysis of the bridge, and it was found that the nonlinearity caused by the sag effect and the loosening of the cables caused a large fluctuation in the axial force in the cables. It was also noted that when the cables on one side of the support tower became slack, the cables on the other side saw a large increase in tensile forces.

Leech (2003) analyzed and modeled the splices that are used to create end terminations in synthetic ropes. The loops are how the SCEDs would be attached to the structural frame. When the ropes are stretched under loading, the individual components of the rope are tightened and this increases the splice integrity. However, the strength of the rope is controlled by the construction of the loops, so it is necessary to ensure that these splices are stitched correctly.

1.2.3 Shock Analysis

The majority of the analytical methods and equations that were used in the present study to analyze the shock that the snap loads exert on the rope were taken from the preceding research by Pearson (2002). However, because this new research expanded upon the work that was previously done, some additional material is reviewed.

Chopra (2001) defines an impulse as a large force that has a very short time duration. The snap load is an impulsive force that is caused by the sudden tightening of the rope. The area beneath the force-time curve is also known as the impulse. The force values from the snap load were recorded for each experiment and, when plotted versus the displacement of the rope, formed what is known as a hysteresis loop. Hysteresis loops are associated with the energy dissipation of a system, and the area inside them is commonly used to determine how much energy is dissipated.

Wu et al. (2003) examined the behavior of steel cables under snap loads. For this work, the axial displacements of the cables were measured from the zero stress condition. This corresponds to the point right before the impulse occurs.

Meirovitch (1967) discussed different methods used to analyze vibrations. Vibrations are transmitted through an object in the form of stress waves. These waves travel at a very high rate of speed and move back and forth between the ends of an object until the vibrations have ceased. A cycle is defined as the interval of time during which one complete performance of a vibration occurs. For this research, the complete progression of a rope from the slack condition to the taut condition and back to the slack condition is defined as a cycle. A pulse is defined as a brief variation of a quantity whose value is usually continuous. A snap load causes a rope to experience both a force pulse and an acceleration pulse when it becomes taut.

Goldsmith (2001) investigated the behavior of colliding solids. One case that was examined dealt with a rod that was suspended from the top and a falling solid that slid down the rod and impacted an end plate. Stress waves were present in this experiment and they traveled up and down the rod. These waves transferred the force from the end plate back to the support. As a result of these stress waves, the force that was recorded at the top of the rod is often much higher than that which is recorded at the bottom.

To validate the data that was obtained analytically from the drop tests, it was desirable to compare it to several theoretical equations. Lalanne (1999) experimented with free-fall impact machines that decreased the velocity of a test item through a shock and/or a change in direction. Shock is defined as a vibration excitation with a short duration that occurs when a force, position, velocity, or acceleration is abruptly modified. The shock was applied to a free-falling test item when it impacted a rubber block, which caused the item to decelerate and rebound. Several equations were taken from this source and used to calculate theoretical values for the stiffness, impact velocity, and maximum displacement of the ropes.

1.3 Objective and Scope of Research

The objective of this research is to analyze how synthetic fiber ropes behave and change when subjected to a series of snap loads. The data that was obtained from this and preceding research was used to create a mathematical model that will be used in finite element modeling of a structural system that is equipped with Snapping Cable Energy Dissipators (SCEDs). This thesis is the second part of a multi-stage research project whose goal is to prove the benefits that SCEDs can provide for structures that are subject to dynamic loads caused by earthquakes.

Chapter two of this thesis is an overview of the previous research and the analyses that were performed on that data as a part of this research. The results from these analyses are also discussed in this chapter.

Chapter three focuses on the preliminary work that was done in this research. This includes a description of how the research was developed and the reasoning behind it, the setup of the new tests, and the details of the testing procedure.

Chapter four is a detailed description of the analyses that were performed on the old and new test data. This includes the classification of several phases and points within the snap loading cycle, the quantities that were obtained experimentally and through analysis, the energy dissipation properties, and the theoretical values.

Chapter five discusses the results of the analyses that were performed on the tests that were conducted as part of this research. A comparison of the results for both stages of this research project is also discussed in this chapter.

Chapter six concentrates on the development of the mathematical model and the results that were obtained from it. The force, velocity, and displacement data from the Follow-Up Tests and New Tests were used to create a mathematical equation that characterizes the behavior of a rope during a snap load.

Chapter seven is a summary of the work that was done for this project and the conclusions that were made from it. This chapter also includes recommendations for the next stage of the research project.

Appendix A consists of tables and graphs that were constructed from the results of the analyses performed on the previous research data and the Follow-Up tests. Appendix B contains tables and graphs from the analyses of the current research data. Appendix C includes the tables and graphs that were made from the results of the mathematical model.