Chapter 1

Introduction and Literature Review

1.1 Introduction

Engineers have proposed numerous designs that mitigate the effects of an earthquake on a structure. Early designs focused extensively on saving lives, with little or no concentration on damage control. Present designs are now focusing on limiting the structural damage caused by an earthquake so that the structure may continue to be used (Levy et al., 2001). Ground shaking caused by an earthquake may induce a large amount of energy into a structure. This energy can cause major structural damage and must be removed in order to maintain the structural integrity of a building. A type of passive control device is proposed using slightly slack cables. When a cable transfers from a slack (loose) state to a taut (tight) state, energy is dissipated. This transition from a slack state to a taut state causes the cable to snap. The tension that builds up during the taut state is referred to as a snap load. A cable can also provide stiffness to a system because the relative displacement between the ends is restricted. This passive control device will be referred to as a snapping-cable energy dissipator (SCED).

The purpose of this research is to collect experimental data on snap loading of synthetic fiber ropes. Various types of cables were tested under dynamic loading. Synthetic fiber ropes of different material make-up, length, and diameter were fixed at one end and attached to a weighted falling plate at the other end. An accelerometer was used to measure the acceleration of the falling plate during the slack and taut conditions of the cable. This acceleration was integrated with respect to time to obtain the change in velocity during each slack/taut transition. Another integration provided the displacement of the plate.

1.2 Literature Review

1.2.1 Seismic Control Techniques

There are many techniques that have been hypothesized and used in the mitigation of seismic forces on structures. Each technique can be categorized as passive, active, or semi-active. Passive control techniques do not need an outside source of energy. This technique is especially attractive because earthquake ground motions often disrupt the power supply to a structure after the first few seismic shocks. Active control techniques require some source of energy in order to dissipate the ground forces induced on a structure. Semi-active control techniques involve the extraction of energy from a system without adding any outside mechanical energy. The extraction is accomplished by dynamically varying the properties of the system.

Hiemenz and Wereley (1999) discuss the utilization of magnetorheological (MR) and electrorheological (ER) dampers in response to seismic ground motion. It is stated that most passive and active control techniques have two main goals. These goals are to add damping to the structure and/or increase the flexibility of the structure. The two techniques stated above can be divided into three main categories. The first of these categories is base isolation in which the period of the structure can be increased and the seismic energy transmitted to the structure via ground acceleration can be damped before it can affect the structure. Another category discussed is a Tuned Mass Damper (TMD) system in which ground motion can be offset by utilizing a mass-spring-damper at the top of a structure. The third category involving the two control techniques is a bracing system. This system utilizes dampers or actuators between successive floors to limit interstory drift. All three of the categories mentioned above can be applied to a structure both passively and actively. The bracing system can be retrofitted to existing structures, which makes this type of mitigation device very attractive.

MR and ER dampers are semi-active control techniques that employ magnetic and electric fields to dampen seismic forces. These fields, when applied to a Newtonian fluid, cause an increase in the yield stress of the fluid. This increase in yield stress causes an increase in yield force of the damper. These dampers require a low energy source and can be powered by batteries in the event of a loss of power. If there is a loss of battery power as well, these dampers still have a low damping level that will allow some of the energy to be dissipated. Tests have shown that MR and ER dampers perform best when placed at low levels of the structure and/or at all floors.

Newman (2001) discusses various devices that dissipate seismic energy within structures. Many engineers provide points of weakness in a structure that are designed to yield or deform in a controlled manner. These points of weakness absorb seismic energy as particular members transfer into the inelastic region. This process is also known as hysteretic damping. An eccentric braced frame system allows the mid-section of a beam to yield and absorb the seismic energy placed on a structure. Another example of a hysteretic damping device is known as a dog-bone moment connection. This device utilizes a weakened section of a beam (near a column) to yield under load. These two strategies may be difficult to use in existing buildings, and the large deformations that can result may be damaging to a building's function.

Another type of energy-dissipating device is a fluid inertial damper. This type of damper uses viscous liquids under a controlled volume to dissipate energy. Many variations of this damper have been designed and implemented in several buildings. All variations have essentially the same concept for dissipating energy. Normally, a piston rod (carrying the load from the structure) is encased in a cylindrical container and allowed to move in one direction. The viscous liquids can be compressed into multiple chambers by the movement of the piston rod. A pressure difference develops between chambers and is essentially proportional to the damping force developed by the fluid. Fluid inertial dampers are used in different types of bracing systems as well as base isolation design.

Other types of dampers include viscoelastic dampers, hysteretic dampers, and friction dampers. Viscoelastic dampers dissipate ground motion by way of a friction release between stacked plates that are separated by an inert polymer. This type of damper will also increase the stiffness of a structure, which may or may not be beneficial. Some types of hysteretic dampers utilize curved steel plates that yield under earthquake loading. This yielding process dissipates the energy placed on a structure. Friction dampers produce a constant damping force from steel plates sliding against each other. All of the dampers discussed in this section are varieties of passive dampers.

In essence, most seismic isolation systems intend to increase natural periods of a structure. By increasing natural periods of a structure, the seismic forces induced on the structure are reduced. A larger natural period will also lessen the probability of resonance between the structure and the seismic ground motion. Resonance can be described as a condition when the forcing frequency applied to the structure is the same as one of the structure's natural frequencies. Increasing the natural period of a structure may also increase the lateral drift. In order to counteract an increase in lateral drift, the amount of damping or stiffness must be increased in a structure.

Tremblay (2001) explains that concentrically braced frames (CBFs) are increasingly becoming one of the more popular alternatives for improving the seismic response of structures under earthquake loading. Early designs utilizing CBFs were very cost efficient and simply designed but lacked the ability to resist ground motions in the inelastic range. This issue has been dealt with extensively in recent years and engineers can now utilize this form of seismic control system in high seismic regions. The improved CBF system is still cost effective and is able to achieve the strength and stiffness requirements needed for the inelastic range of motions.

Beams and columns are required to carry the gravity loads applied to a structure, while lateral bracing is required to resist lateral loads. It is required that inelastic deformations under seismic loading only take place in diagonal bracing members so that the integrity of gravity load carrying members of the system is not compromised. The braces must be adequately designed to handle multiple cycles of loading without premature fracture occuring. The amount of energy dissipated depends on the slenderness, cross-sectional shape, and effective length of the brace. Various types of bracing configurations can also affect the inelastic seismic response of a structure. Examples of these configurations are diagonal bracing, Chevron and V-bracing, tension-only bracing, and tension and compression bracing. AISC *Seismic Provisions for Structural Steel Buildings* (AISC 1997) specifies the allowable bracing configuration for the two concentrically braced frame systems (Special Concentrically Braced Frames, SCBFs, and Ordinary Concentrically Braced Frames, OCBFs).

Levy et al. (2001) discusses the use of friction damped slotted bolted connections (SBCs) in steel frames as a means to mitigate seismic energy. This type of friction damper is relatively easy to construct and does not use any special components that cannot be bought commercially. Another attractive quality of this damping system is the ability to retrofit existing structures. The connection joins two parts of a concentrically braced frame and allows slippage of the bolts, which in turn allows seismic energy to be dissipated through friction. Steel or brass pads are generally used between the faying parts of the connection.

The previously mentioned base isolation technique typically employs laminated rubber-like materials inserted between a structure and its foundation or support. The most commonly used isolation technique today involves laminated elastomeric bearings. These bearings consist of layers of rubber and steel stacked on top of each other. The rubber layers allow the structure to be reasonably flexible in the horizontal direction, which increases the period of the structure. Essentially, the amount of structural damage from seismic ground motion is greatly reduced because the inter-story drift is greatly reduced (Salomon et al. 1999). The base isolation system is also widely used to protect bridge structures from seismic ground motion. The rubber layers are vulcanized to steel plates and placed between the superstructure of a bridge and the substructure. Originally, this system was used to counteract dimensional and shape changes of a bridge under temperature changes, but now has found extensive use in mitigating seismic energy (Feng 1999).

Different control techniques for seismic energy dissipation have been proposed over the past few years. All of these techniques have saving lives as the number one goal. Other goals include limiting the amount of structural damage, having the ability to retrofit existing structures, ease of construction, and cost efficiency. The SCED is a new concept for seismic control systems and has many attractive qualities. These cables are relatively inexpensive, easy to install in both new and existing structures, and can be used with other energy dissipating devices.

1.2.2 Material Properties

The amount of research done on wire rope far outweighs that on synthetic fiber ropes, especially in the area of structural engineering. It has been shown through research that the endurance of synthetic fiber ropes is much better than for steel wire ropes (Banfield 1998). Triantafyllou et al. (1995) states that synthetic cables are significantly better than steel cables in certain situations because they are much lighter and can absorb dynamic motions through slight elongation without large amounts of dynamic tension. Other advantages of synthetic fiber ropes are ease of handling and safety. Wire ropes or cables behave similarly to fiber ropes or cables under tension loading through the elastic region. One of the attractive properties associated with ropes is their ability to resist large axial tensile loads as compared to torsional or bending loads (Costello 1978). Krishna (2001) believes that the most attractive property of ropes is the very high strength-to-weight ratio.

According to Samson Rope Technologies (1997), vegetable fibers were the only materials available to rope manufacturers until the 1940's. These fibers included manila, sisal, hemp, and cotton. Nylon was the first synthetic fiber manufactured in the 1940's and spawned the invention of all other synthetic fibers such as polypropylene, polyethylene, polyester, Kevlar, Spectra, Vectran, and Dyneema. Both vegetable and synthetic fibers are used in ropes today and each fiber has its own unique material properties that play an important role in the strength and stiffness of a rope.

The three most common conventional rope materials are nylon, polyester, and polypropylene. Nylon has the lowest modulus of elasticity, but it is the strongest of all the rope materials when dry. Under cyclic tensile fatigue loading, polyester is very durable. Polyester also has a very high stiffness modulus (Flory et al. 1999). Nylon and polyester are both stronger than polypropylene, but polypropylene is most commonly found in marine applications because it is relatively inexpensive and it floats (Flory and Banfield 1999). Polyethylene is another common rope material, but is not commonly used in high load situations.

Flory et al. (1999) discusses high-modulus fibers, which make up another class of synthetic fiber ropes. These ropes have much higher modulus of elasticity and breaking strength than the conventional ropes discussed above. These qualities allow high-modulus fiber ropes to have very high tenacities, which is a measure of strength per linear weight. The three most common high-modulus rope fibers are aramid, high modulus polyethylene (HMPE), and liquid crystal aromatic polyester (LCAP) or Vectran. Aramid fibers, also known as Kevlar, were first used for mooring applications in the 1970s and have since expanded to play a very important role in many marine purposes. HMPE is made up of high-density polyethylene. First introduced commercially in the mid 1980s, HMPE fibers are lighter than water, which allows them to have a higher specific strength than aramid fibers. Dyneema and Spectra are both forms of HMPE fibers, which are formed using a gel-spinning process. Some important properties of HMPE fibers are their low melting points, limited axial compression fatigue problems, low coefficient of friction, and excellent abrasion resistance. LCAP fiber (Vectran) was introduced in the early 1990s and is successfully being used in high-performance cables. While LCAP fiber is more expensive than both aramid and HMPE fiber, advances in technology should relinquish a more economical process for producing these fibers, thus making it more competitive with the other two fibers. The U.S. Air Force has recently introduced one other class of fiber called polybenzoxazole (PBO). This fiber is more complex and more expensive than the other three fibers, but has a higher modulus and higher strength than the other synthetic fibers mentioned above.

There are also some disadvantages associated with the use of high-modulus fiber ropes. Hooker (2000) gives two potential disadvantages of using these ropes. Given that these ropes have such high tenacities, the size of the rope (diameter) is generally smaller than that of an equal strength wire rope. The smaller size permits them to be more susceptible to damage from leads (dock anchors) that are defective. Another disadvantage can be the high stiffness that these ropes possess. Many applications that involve the use of high modulus fiber ropes require a considerable amount of elasticity. Some manufacturers have made modifications to these ropes by combining polyester fiber strands at each end for soft connections.

1.2.3 Rope Construction

Although often used interchangeably, cables and ropes are different. A cable is a flexible tension member that is made of one or more groups of strands, wire, or rope. Alternatively, a rope consists of a number of helically wound strands around a central core that is composed of a strand or another rope (Podolny 1986). Krishna (2001) explains that the extensional stiffness and elasticity of a rope or cable depends on the size and amount of strands used in construction as well as the method of construction. Ropes do not have a physical bonding between the individual components within the rope (Wu 1993). Therefore, each individual strand is allowed to move independently (to a certain degree) with respect to the other strands.

Ropes are not one solid entity, but rather a culmination of similar fiber components. Flory et al. (1989) and Leech (2002) explain that the basic elements that make up a rope are fibers, yarns, and strands. Thousands of fibers are compiled to form yarn. Numerous yarns are twisted together to form plied yarns, which are then compiled together to form rope yarn. Several rope yarns are twisted together to form a strand. These strands can be twisted or braided together to form rope. Figure 1 illustrates the components that act as a single rope. Ropes that are twisted together often have a central core around which the strands are twisted. The central core's main purpose is to provide stability for the individual strands so that they maintain their position under loading (Scalzi 1969). The twisted form of construction is often referred to as wire rope construction or WRC (Flory et al. 1999).

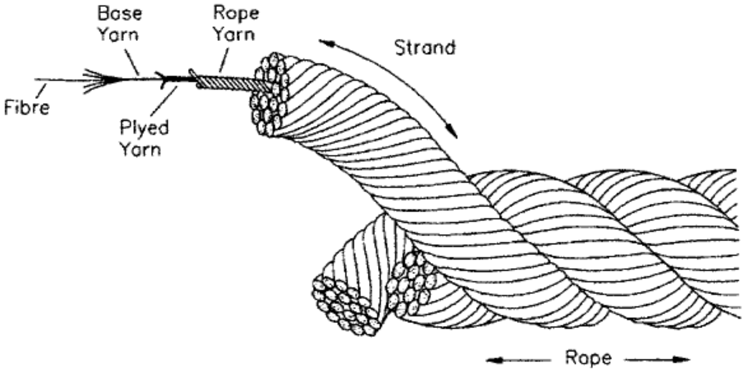

Figure 1.1 Basic Elements of a Rope. (Courtesy of Elsevier Science. Leech, C.M., 2002)

There are several different twisted forms of rope construction. Scalzi et al. (1969) gives a detailed explanation of each of these forms. Scalzi explains that the “lay direction” in a strand is the direction in which the outer wires twist around a strand as seen moving back from the spectator and viewed from above. Two different types of lays are considered in rope construction. In regular lay construction, the lay of the individual rope yarns in each strand are opposite the lay of the individual strands in the rope. In lang lay construction, the lay of each component (i.e., the rope yarns and the strands) is in the same direction. Within these two types of lays are the directions of the strands that make up the rope. Therefore, right lay and left lay can be used to describe both regular lay and lang lay constructions. When subjected to a tensile load, twisted ropes will have some rotation. Regular lay construction is more stable and less likely to rotate than lang lay construction because the rope yarns are oriented in the opposite direction of the strands.

In order to bypass the rotation that occurs in twisted ropes under tension loading, braided rope construction is often used. Flory et al. (1999) explains that although braided ropes can be considered torque free, they are not torque tolerant. Under an applied rotation, the forces are only transferred to half the strands. The most common braided ropes used in industry and marine applications are the 8 strand and the 12 strand. Other types of braided ropes used are the 6 strand, 18 strand, and 36 strand. Leech (2002) further identifies common braid constructions as tubular braided or round braided, solid braided or American braided, and eight-strand plaited. Tubular braided rope (8 strand and 12 strand) is the most common construction type. This type usually has a central core around which the strands are braided.

This type also reduces the amount of empty space in the tube by using a large number of smaller strands braided very tightly. Another type of braided rope discussed by Wu et al. (1995) is the double-braided rope. This type of rope construction consists of a core rope and a sheath. These two layers are separable and are made of numerous braided strands. One advantage of braided ropes given by Hooker (2000) is the simplicity of splicing for an end termination. Also, cover damage is not a concern in braided ropes, but they tend to abrade and lose strength after initial use.

1.2.4 Frictional Effects

Many papers have been written on frictional losses in a rope or cable under tension loading. A rope responds to tension loading and unloading by allowing friction between each individual strand in the rope to be released (Costello 1997). The friction between strands causes energy to be dissipated, which can in turn dampen a structure. As the displacement between the ends of a rope increases, the individual strands that make up the rope structure slide against each other and/or a central core. Some of the papers dealing with frictional losses will be discussed in the following paragraphs.

In Banfield and Casey (1998), an evaluation is made on the fiber rope properties for offshore mooring. They focused on the fact that a mooring system must have enough axial stiffness to keep a system from drifting too far off its original position while being able to avoid failure due to overload. Axial stiffness can be described as a measure of resistance to rope elongation. Varying tensions can result in a change in the mechanical properties of rope as well as fatigue damage. Banfield and Casey conducted tension tests on three types of ropes (two aramid types and one polyester type). In all three types, axial stiffness decreased with increased load. In another test, a polyester wire rope, an aramid fiber rope, and a polyethylene rope were tested for modulus effects in tension. Dividing the test length by the area and multiplying by the gradient of the loading curve determines the modulus. As the load range increased, the modulus for the fiber rope and the wire rope decreased. Hysteresis tests were also conducted on various wire and fiber ropes. Hysteresis is a measure of energy dissipation by a rope during a fatigue load/displacement cycle. The test results show a fairly constant hysteresis throughout the test until failure is imminent, at which time the hysteresis increases. Banfield and Casey concluded that the cyclic loading period, the load range and mean load, material degradation, construction and geometric properties, and the material/scale could influence rope mechanical properties. They also concluded that the fiber rope and the wire rope have very similar performances under axial fatigue.

Banfield and Hearle (1998) discuss the dissipation of energy under cyclic loading. Energy is dissipated in part by the friction between individual fibers and the material losses within each fiber. Huang and Vinogradov (1996) address the fact that frictional damping in cables is caused mainly by dry friction between fibers, while a small amount is dissipated through individual fiber losses. This is mainly due to the relatively small material viscosity of an individual fiber. Twisting and bending deformations cause slipping between separate fibers in a rope or cable. It is this slipping that allows energy to be dissipated.

Leech (2002) explains that friction in synthetic fiber ropes can be categorized as either inter-friction or intra-friction. These two categories can be further broken down into more precise cases of their respective friction modes. In rope construction, the countless fibers that make up the strands are in contact with each other. As tension is applied to a rope, the contact of these fibers becomes more extreme. The energy dissipated by a single fiber due to slipping is very small, but in unison with the numerous other fibers, the energy dissipation may be very significant. These contact forces that develop between individual fibers have been the subject of several studies. The friction hysteresis related to contact forces is dissipated through material fatigue, heat, and component wear and abrasion.

Inter-friction can be described as friction caused by the slipping of rope components with respect to each other. This contact or bearing force is normal to the slip surface. Leech describes four modes of inter-friction. The first of these modes is called the axial slip mode in which the friction is caused by the stretching and/or twisting of a rope. Friction in this mode occurs between components of the same layer within a rope. As a rope is loaded in tension, the friction acts axially in opposite directions along adjacent components. The second mode described by Leech is the component twist mode. This mode also acts between components of the same layer, but is caused by the torque associated with each individual fiber rotating about its own axis. The torque associated with each fiber must be resisted by friction between adjoining fibers. Another inter-friction mode discussed is called scissoring. Scissoring occurs between fibers that are not in the same layer within a rope. Friction develops when one component slides over another in braided or plaited ropes. The contact area changes with varying applied loads. Under increasing loads, the angle between adjacent strands decreases, which causes the contact area to increase (i.e., the strands slide more parallel to each other). As the contact area increases, the contact pressure and friction increases, thus more energy is dissipated. The fourth mode described by Leech is called the sawing mode in which one strand slides over another strand in another layer. The opposite strands slide nearly tangential to one another, so the contact area is relatively small. This mode is similar to the scissoring mode except that there is little or no rotation between strands.

Intra-friction develops via internal deformations within the individual fibers of a rope structure. Each individual fiber in a rope can experience elongation and/or contraction under loading. When each of these fibers returns to its natural state, energy is dissipated under the cyclic loading. One of the intra-friction modes described by Leech is called the dilation mode. Under load, fibers experience a change in cross-sectional area. When the load is removed, the area will recover to a certain extent back to its original size. Hysteresis from the loading and unloading is due to internal friction within a fiber. Another mode described is the distortional mode in which a fiber is permanently distorted both in shape and area due to loading and unloading. Individual components cannot return to their initial shape or area due to residual strain in the structure. Once again, internal friction causes hysteresis in the rope structure.

Labrosse et al. (2000) investigate the frictional damping properties of axially loaded metallic cables consisting of one central wire helically wrapped by one layer of wires. The damping properties of a cable due to friction are controlled by the contact of internal wires and the geometry of the individual strands. Tests were conducted so that the outside wires were only touching the central wire core. Their results proved that the total pivoting friction is a much smaller source of dissipation than the total slip friction. Therefore, whenever interwire sliding and interwire pivoting are both present, the friction associated with the pivoting can be neglected with respect to cable damping effects.

Hobbs and Raoof (1996) and Kumar and Botsis (2001) discuss the contact phenomena that occur between fibers in a rope or cable. These contact phenomena are very similar to the contact forces discussed by Leech (2002) and Labrosse et al. (1996). Two types of contact occur under tension loading in a spiral stranded rope or cable. The first of these types is the contact between parallel strands in the same layer. Line-contact forces occur when adjacent strands in a spiral stranded rope or cable slide relative to each other, and can be considered to be a large source of energy dissipation when integrated over an entire rope structure. The other type of contact discussed occurs between different layers in a spiral strand and can be called point or trellis contact. Strands in different layers cross at an angle, which produces a point contact rather than a line contact. Trellis contact forces are considered to be much lower than line-contact forces.

Hooker (2000) discusses recent developments in braided high-modulus ropes, such as pre-stretching and rope impregnation. Pre-stretching can increase strength and stiffness significantly. This technique usually involves multiple static load cycles up to a certain percentage of the rope’s breaking strength. The percentage varies based upon the material type of the rope. The permanent elongation associated with pre-stretching is often referred to as constructional elongation. Each individual strand will “bed in”, which decreases the diameter of the rope. “Bedding in” is a process in which the fibers and strands realign themselves into a tighter configuration, which increases stiffness. Rope impregnation increases the durability of a rope. This involves impregnating the rope with various materials to increase friction between strand fibers. Materials such as polyurethanes and bitumastic matter help to evenly distribute axial loads from the outer strands to the inner strands.

1.2.5 Snap Loads

Snap loads occur when a rope or cable goes from a slack (loose) state to a taut (tight) state in a very short amount of time. A cable is said to be slack when the distance between its two ends is less than its natural length. Taut refers to the condition in which the distance between the ends of a cable is equal to its natural length, or the cable is stretched to a longer length. Snap loads reach high values very quickly when the cable is taut and then decrease very quickly once it becomes slack (Plaut et al. 2000). As mentioned earlier, a cable responds to tension loading and unloading by dissipating energy via friction between each individual strand in the cable. The energy dissipation can essentially dampen a system by releasing the dynamic energy applied to a structure from ground motion. Snap loads are very quick and may be very violent. The life of a rope or cable is greatly affected by multiple snap loads due to fatigue of individual fibers under cyclic loading. Snap loads are applicable to many other cable structures such as moored marine systems, cable-stayed bridges, suspension bridges, guyed masts or towers, and cable roofs. All of these systems can undergo dynamic loading and thus experience snap loads.

Wu et al. (1995) and Millette et al. (2001) explore the phenomenon of snap loads and show that such loads may be much greater than quasi-static loads. Millette et al. (2001) discusses the dynamic loading of static lines with respect to personnel parachutes in U.S. military mass tactical assault airborne operations. The nominal strength of a line is described as the strength when loaded to rupture under static conditions. Alternatively, the strength of a line in association with dynamic loading can be called the effective strength. Experiments have shown that the effective strength of a line can be significantly (as much as 50%) less than its nominal strength. This illustrates the violent nature of snap loads and the effect they have on ropes or cables.

Plaut et al. (2001) consider the motions of a buoy moored to the sea floor by cables. They analyze the buoy as a mass connected to a pair of cables in a two-dimensional response of slack/taut cable behavior. Large motions cause the mooring lines of a buoy to become slack. Once the lines become taut again, the condition may involve a “shock” or large tensile force known as a snap load. Plaut et al. describe the rebounding of the buoy, which causes an impact to take place. At the instant the impact takes place, energy is lost. The number of times the buoy transfers from a slack condition to a taut condition affects the life of the connecting mooring line. The axial velocity of the buoy connection at the slack/taut transition also affects the life of a mooring line.

Niedzwecki and Thampi (1991) study the dynamic response of snap loading in marine cable systems under normal sea conditions. Their study focuses on a dynamic model of a rigid body suspended from a multi-cable system in regular seas. This model allows them to investigate the snap load behavior of the model. Cables are flexible and cannot resist compressive forces. Under compressive loading, a cable will become slack until the load is released. If the cable is then placed under a quick tension load, the cable will experience a severe impact load or snap load. Snap loads are of a non-linear nature and are more easily predicted by time domain simulations. Niedzwecki and Thampi consider single-degree-of-freedom and multiple-degree-of-freedom systems. They found that there are certain patterns to the timing of the snap loads and that the cables should be able to withstand multiple snap load cycles without breaking. The successive snap loads clearly cause a reduction in the useful life of the cables, but multiple snap loads can be tolerated before bringing the rigid body to the water surface.

1.2.6 Rope Life and Fatigue

The life of a synthetic fiber rope depends on a number of different variables. Environmental conditions such as temperature, moisture, and sunlight can all affect the serviceability of a rope. The type of fiber that forms a rope can also affect the service life. One of the most important contributors to the life of a rope is the loading to which the rope will be subjected. Clearly, if a rope is subjected to very high loads for an extended period of time, the rope life will be relatively short. On the other hand, if a rope is subjected to low loads for small periods of time, the rope life will be relatively long. Fatigue can also play an important part in the life of a rope. Ropes tend to creep or elongate over time under a constant load. Self-weight can also cause a rope to creep.

Seo et al. (1997) describes research on the wear and fatigue of nylon and polyester mooring lines. Fatigue tests were conducted on low twist nylon and polyester yarns in a dry state. These tests show that the dry polyester has a greater fatigue life than dry nylon based on normalized maximum stress cycles. Seo et al. discuss the hysteretic thermal effects in a tensile cycling test in which the mechanical energy of friction is turned into heat energy. In the case of tensile fatigue, the cycling frequency and the cooling environment determine the amount of thermal build-up in the rope. When a material surface is rubbed across a relatively smooth surface, wear can occur. Interior wear can occur in ropes during tensile cycling when strain differentials along separate rope elements cause relative movement between them. Essentially, this interior wear can cause tensile fatigue of a rope. In durability tests of dry yarn versus wet yarn, nylon exceeded polyester in very high tensions. Once the test tensions were lowered, the polyester wear life surpassed the nylon wear life.

Flory et al. (1989) explains concepts of residual strength and rope life interaction. They conclude that during constant loading, rope failure would occur once the residual strength falls to the cyclic load level. This is a point on the cycles to failure plot. This plot allows engineers to know when to remove a rope from service before failure occurs. Flory et al. also describe four principal modes of rope failure. They are creep, hysteresis, fiber fatigue, and internal abrasion. Constant loading can cause a rope to increase in length permanently. This increase in length is called creep. With respect to the different fiber ropes, creep is of little significance in polyester and aramid fiber ropes; it has slightly more significance in nylon ropes; and it can be significant in polypropylene ropes. There are two causes of hysteresis in fiber ropes. Relative slippage between separate elements causes friction to build up, which causes a loss of energy. Another cause of hysteresis results from the straining of individual fibers within the rope. Crack propagation in a single fiber, similar to metal fatigue, can lead to fiber fatigue in a rope. Also, fiber damage can occur when fibers buckle in compression. Compression fatigue is a result of a fiber being restrained among a group of tensioned fibers, but not loaded as high as the surrounding fibers. Internal abrasion occurs when the various rope elements slide relative to each other. This causes internal wear on a rope. As the wear progresses, individual fibers may fail until ultimate rope failure occurs.

Flory (1996) discusses fiber axial compression fatigue in ropes, cables, and other tension members. Axial compression fatigue occurs during tension unloading as some fibers go into compression while a majority of the fibers are relaxed. Other situations, such as a rope being bent or rotated, can also cause this phenomenon. The reason that some of the fibers go into compression is that the lengths of all fibers are not the same and some fibers become slack and go into compression before most of the other fibers become slack. Under tension loading, not all fibers share the same load. Upon unloading, the shorter fibers may still have some tension load in them while the longer fibers, which had the least amount of tension under full load, go into compression. Thus, the longer fibers may endure some axial compression fatigue and ultimately fail. Although axial compression fatigue usually does not lead to rope failure, it can increase the chances that the rope will fail due to other causes such as other forms of fatigue. Axial compression is only applicable over a very short length of fiber or when the fiber is firmly constrained radially. Axial compression fatigue differs from tension fatigue. Crack propagation fatigue is a form of tension fatigue that is progressive. As tension cracks become more prevalent in fibers, the rate at which fatigue grows increases. However, fiber axial compression fatigue is regressive. This simply means that as the fatigue damage increases, the rate at which the damage occurs is reduced. As the longer fibers fail due to axial compression, further axial compression stops because the other slightly shorter fibers do not become slack after the initial fibers fail. Studies have shown that high modulus fibers are more prone to axial compression fatigue than low modulus fibers. Also, fibers with high friction coefficients tend to have a greater chance for axial compression fatigue. The main factors influencing fiber axial compression fatigue are rope structure and strand structure.

1.3 Objective and Scope of Research

The objective of this research was to obtain experimental results from the snap loading of synthetic fiber ropes. There is very little information pertaining to this type of loading on high-modulus ropes. This thesis will provide valuable information that will be used in further research pertaining to snapping-cable energy dissipators. The rope properties that were found in this research will be used to create a mathematical model of each rope's behavior under dynamic loading. Finite element modeling of these ropes and physical testing of the ropes in scale structures will also be part of this complete study.

Chapter two of this thesis will elaborate on the properties associated with synthetic fiber ropes in general as well as the specific ropes that were tested. End terminations will be discussed as well as other information that was found from discussions with people in the rope industry. Each rope that was tested will be discussed in detail and a figure will be displayed in order to further show the rope's details.

Chapter three will give a detailed account of the steps taken to arrive at the testing set-up and procedure that was decided upon. The drop tower that was used to test the ropes will be described also. The data acquisition system that was used during the tests will be described in detail as well. Both the static test procedure and the dynamic snap load test will be discussed along with the reasons for conducting the tests in the manner in which they were carried out.

Chapter four will give and explain the results of both the static tests and dynamic tests. Also shown in this chapter are example plots of the results and some comparisons between different drop tests. A complete set of dynamic test plots can be found in Appendix B.

A brief summary and conclusions will be given in Chapter five of this thesis. An overview of the ropes that were tested and the testing procedure will be revisited, while further explaining the reasons for the procedures. All results will be discussed in more detail, and the need for further research will be explained.