Rescue System Mechanics, Interim Report

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Abstract

Rope systems used by wilderness and urban rescue teams in the access and extrication of injured and stranded persons often result in forces in excess of the primary load. Examination of the mechanics of these systems can aid in the quantification of these forces, identify key points in the systems where large increases in force are generated, and aid in the construction of more efficient and safer rescue systems. In an effort to comprehensively quantify the resultant forces created in the use of rope rescue systems, a three-part study was conducted. This study involved the analysis of common systems using static and dynamic mechanics of friction, the creation of a mathematic (computer) model of the maximum forces in rope systems, controlled-environment system testing in a laboratory environment, and full-scale field-testing in actual rescue environments. Additionally, in order to quantify variables needed in the modeling of rope systems, coefficients of friction for commonly used rescue rope on various materials were measured. This paper summarizes the results of the mechanical analysis, mathematic modeling, and controlled environment testing.

Introduction

To improve rope rescue system safety and efficiency, a project was undertaken to quantify the static and dynamic forces generated in the application of commonly used systems. The full scope of the project and the volume of data collected are too large to present in full in this format. Therefore, this paper provides an overview of the project to date with samples of representative results.

This study used mathematical models, bench testing of scaled-down systems in a laboratory environment, and full-scale field-testing. Preliminary predictions indicate the forces generated in the real-world application of raising systems are much greater than commonly assumed. Controlled-environment and field-testing were done to verify the results of the modeling by using a defined test protocol to enable repeatability. Additionally, friction coefficients, which are needed to accurately calculate system forces, were measured.

Background and Need

The hypothesis of this study is that simple variations in system configuration can result in a more efficient system with a wider margin of safety. Some previous work touched on these possibilities but did not discuss the full implications or perform extensive field verification (Storage date unknown, Rowe 1996, Attaway 1999). Calculations of forces in rope rescue systems, accounting for contact-displacement angle and coefficients of friction, indicate changes in either the angle or the friction, or both, can have dramatic results in the force required to raise a load. In addition, some traditional methods used for altering these variables are prohibitively heavy and large. Initial calculations by Attaway (1999), based on a derivation of the drum friction (capstan) equation (Shames, 1967), showed that very high forces can be generated with relatively low primary loads. The capstan equation used in this study is shown as in equation 1 (eq.1)

Eq.1 $$\mathbf{T_2=T_1}\boldsymbol{e}^{\mu\theta}$$

where: T_2 is the resulting tensional force
T_1 is the initial tensional force
μ is the static coefficient of friction
θ is the contact angle in radians

The complete derivation of the equation can be found in previous work by Attaway (1999). Equation 1 predicts the resulting tensile force for impending motion given the initial tension, the contact angle, and the static coefficient of friction. Forces predicted by Eq 1 were calculated for varying primary weight, contact angle, and edge friction. A graph showing the results of these calculations are shown in Figure 1.

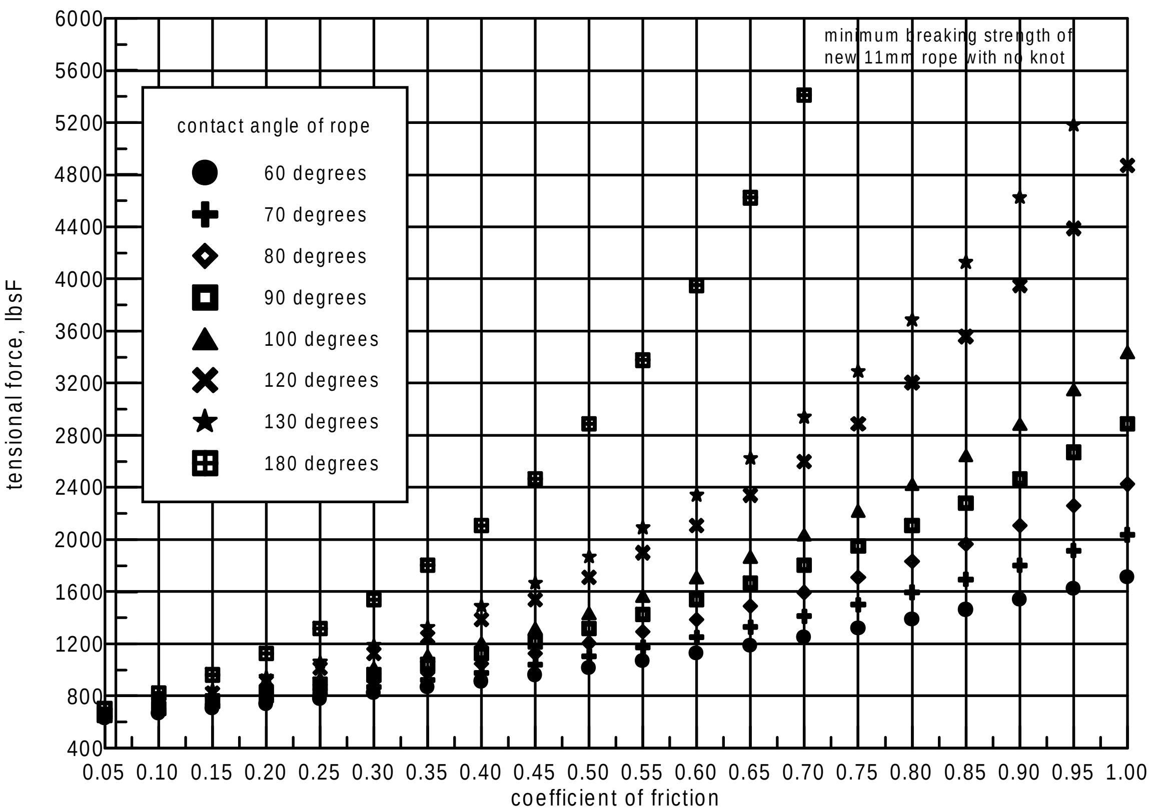

Figure 1. Graph of calculated forces generated at varying angles and friction, 600 lbsF. primary load.

Coefficients of Friction

Coefficients of friction describe the resistance of a material to slide over another material. For a given material, the static or dynamic coefficient of friction will differ for varying secondary materials and whether lubrication conditions are present, e.g. lubricating oils, water, etc. Due to space constraints, this paper will forego a detailed discussion of the theory of frictional interactions and focus more on the practical application.

Previous studies have relied primarily upon frictional values for nylon or polyester generated by the textile industry. These values are typically reported as nylon on steel, and generated for use in sewing machines and loom devices. In order to fully understand and predict actual rescue system forces, coefficient of friction data must be obtained for the types of materials used in rescue systems.

Static coefficients of friction were measured for varying diameters of static kernmantle rope manufactured by Pigeon Mountain Industries (PMI), Bluewater Inc., and Sterling Rope Manufacturing. Values were calculated using both the standard inclined-plane method and modified version of the ASTM C 1028-96 horizontal dynamometer pull-meter method. The inclined-plane method is a standard experiment in mechanical physics involving tilting a platform to the point where movement of a material first occurs. The tangent of the angle of the plane at the point of movement is equal to the static coefficient of friction. For this study, this method was performed using 4 x 10 x 1-inch test block. Ten wraps of each rope type were secured around the block with the ends secured on the up, or dorsal side of the block. Separate test cycles were run on each test assembly using different loads. Each test was performed using the weight of the test block itself and duplicated under a 25-lbsF. test load directly on top of the test block.

The horizontal pull meter method involves the application of force to a test assembly in contact with the test material. This method was developed for use in determining the slip resistance of flooring materials. However, its application is similar to that required for this study and provides a repeatable method of testing in-situ materials, such as rock outcroppings and guardrails. The ASTM standard calls for the use of a 50 –lbsF. test load to be placed on the test material. For this study, the test has been modified to use a 25-lbsF. test load to provide consistent variables between the test methods. This resulted in a pressure application of 0.63 pounds per square inch (psi) to the test block or 0.063 psi per rope strand.

These tests were performed on 8mm, 9mm, and 11mm PMI EZ bend, 11mm PMI Max-wear, 11mm Bluewater static, and 11mm Sterling static. Equal lengths of new/unused and older/used ropes were tested. In this phase of the study, no polyester ropes were tested. Static friction coefficients were measured on three samples of varying grains-sized sandstone, four samples of limestone, granite, canvas, 1,000 denier cordura nylon (rope bags), mild steel, stainless steel, galvanized steel, aluminum, high density polyethylene (HDPE), and wood. Measurements were repeated a minimum of twenty times per material pair. Statistically, the values measured for all rope segments by the two methods were identical. The static coefficients of friction appear to decrease as normal force increases. Previous research has noted a pressure dependant relationship between nylon and other materials. A possible reason for pressure dependency may be due to large deformations of the nylon fibers, resulting in the surface characteristics of the rope changing. The values measured for nylon rope on various materials are presented in Table 1. These values are averages of multiple test cycles of a minimum of 20 repetitions each. As expected, the spread of the friction coefficients measured for natural materials, such as various rock types, varied greatly. The spread for a particular sample, however, was low. Variation in natural materials caused a wide range of values provided for some materials. Friction of rock materials appears to be primarily dependent on the induration of clastic materials, the degree of weathering of igneous and biodepositional materials, and the number, size, and hardness of crystals present in a rock.

Table 1. Static coefficients of friction for nylon kernmantle rope.

sandstone	limestone	granite	Cordura nylon	Canvas	Stainless steel	Galvanized steel	Aluminum	HDPE	Wood
0.6-0.8	0.5–0.9	0.5–0.9	0.43	0.57	0.7	0.6	0.7	0.13-.25	0.5

Rescue System Modeling

We developed a mathematical model for the total load in a rescue system to simulate the tensional forces at various points in a given system. The model is based upon applying Eq 1 to the system shown in Figure 2, which shows a schematic cross-sectional view of a typical raise system. Figure 2 also shows a standard 3:1 Z system for clarification, but it is not discussed in this study. The total force at the point of maximum tension is predicted by:

Eq.2 $$\Sigma T_m = \{ [\{ [(m_l + m_{r1})g] \sin\theta \} e^{\mu_1 \beta_1}] + (m_{r2} g) \} [e^{\mu_2 \beta_2}]$$

where:

ΣT_m is the sum of the tensional forces created in the system at the point of maximum tension
m_l is the mass of the litter, subject, and attendant(s)
m_{r1} is the mass of the rope in segment 1
g is acceleration due to gravity
θ is the angle created between the horizontal and the litter load
μ is the static coefficient of friction
β is the contact angle in radians

Equation 2 is based upon the rope touching at two points of angular contact. If the rope is only in contact at one point, then zero values entered for those variables will result in a negation of the second term. If the system has more than two points of angular contact, then the second term can be repeated as necessary. A first approximation of the effects of litter handlers carrying the litter on a non-vertical slope is taken into accounted by the product of the sine of theta and weight of the litter assembly. In a non-vertical environment, a portion of the weight of the litter assembly is transferred through the musculature of the litter bearers, resulting in a pseudo-frictionless travel of the litter over the sloping plane. This factor does not account for the effects of a litter wheel. In a free-hanging vertical environment, where the entire force exerted by the litter is creating tension on the rope, the sine of theta would be equal to 1, and, thus, can be removed from the equation.

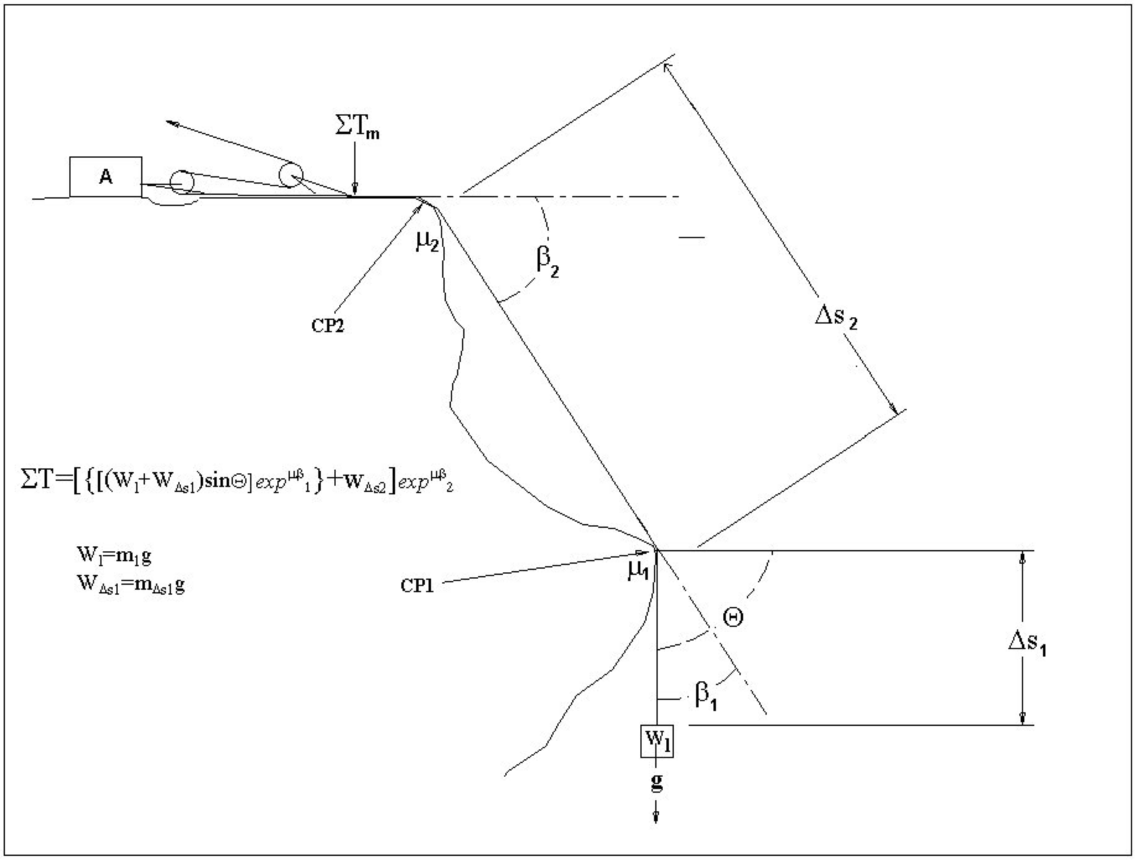

Figure 3. Schematic diagram of a typical rescue system showing the location of variables effecting tension.

Controlled Environment Testing

Following the development of the systems model, a series of laboratory bench tests were performed to validate the assumptions of the model. Laboratory tests measured and observed behaviors of rescue systems in a controlled environment, where friction, contact angles, humidity, ambient temperature, and materials temperatures can be precisely measured. Similar to the friction coefficient measurements, each test in a given configuration was repeated a minimum of twenty times. Bench testing included the use of full-scale new and used rescue equipment. Tests were conducted using various diameters of static kernmantle rope from PMI, Bluewater, and Sterling Rope. The system was tested using a 25-lbsF (0.1 kN) test load. Forces were measured using two 5,000 lbsF (22kN) range S-beam load cells, which were calibrated using the three point method and were recorded at 100 cycles per second (hZ), one 50 lbsF (0.22 kN) strain gage, and a 5,000 lbsF (22 kN) dynamometer. Temperatures and humidity were measured using type-K microbead thermocouples and a thermohygrometer.

Predicted values using Equation 2 for a given test configuration fell within the span of measured values for all tests. The average maximum tensional force value, however, was consistently five to ten percent lower than the model predicted value, while the maximum tensional force measured was generally two to five percent higher than the model predicted value. The difference between the model and the measured results may be due to the model assuming impending motion at all points in the system. This assumption does not account for the dynamic series of movements that take place as motion starts and stops at different points. While this variation is obvious at low test-loads, the significance decreases as the loads increase. Repeated laboratory verification tests show the model predicts the maximum tensional force created in a raise system within the error bounds of the test (one standard deviation). Figure 3 shows a typical graph of three-cycle repetitions of tensioning and slacking during a bench test using 11mm PMI max wear on sandstone with a 120 degree contact angle.

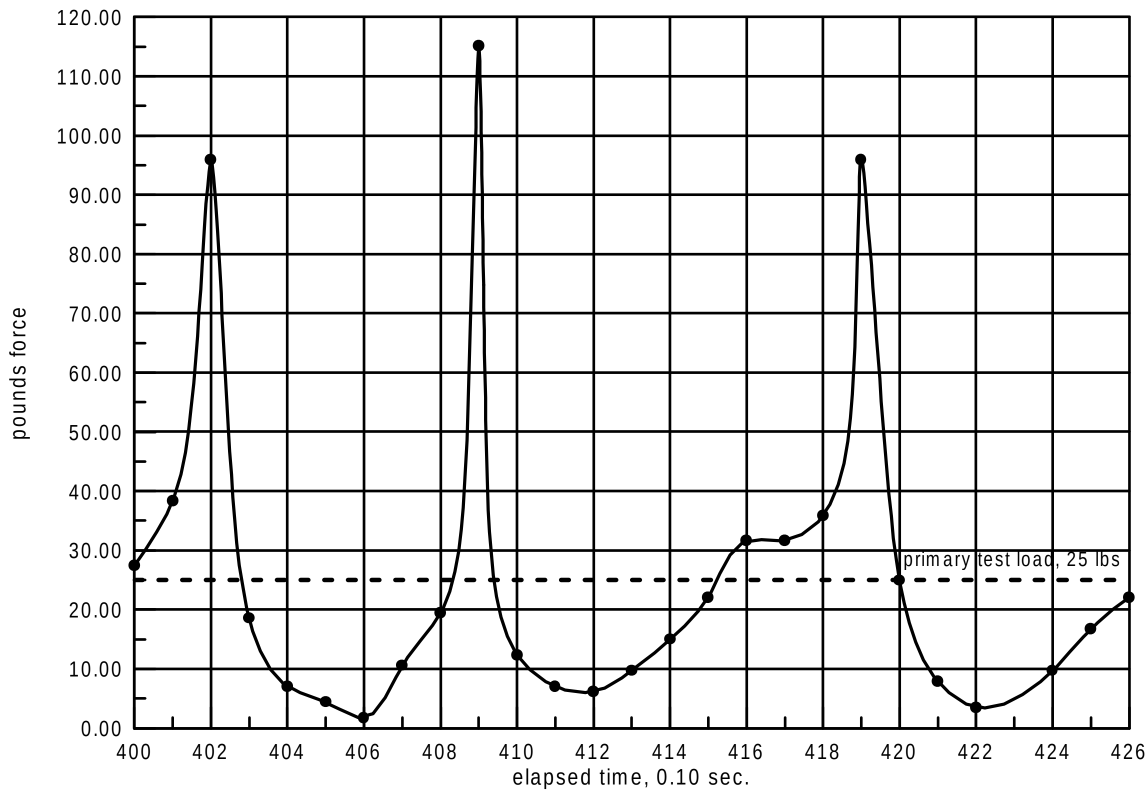

Figure 3. Graph of measured tensional forces generated in a raising system.

While the complete set of collected data is too large to present here, Table 2 presents a representative test run using new 11mm PMI Max wear with an ambient temperature of 91 degrees Fahrenheit and 22 percent humidity. Figure 4 is a graphical presentation of the same data. Figure 5 presents a graph showing the variations in tensional force caused by differing contact angles with a constant friction interaction.

Table 2. Results of laboratory bench testing of simulated rescue systems with 11mm PMI max wear rope and 25-lbsF test load.

edge material	sandstone	HDPE	aluminum	Steel	canvas	Cordura nylon	sandstone	HDPE
contact angle, degrees	90	90	90	90	90	90	120	120
model prediction lbsF (kN)	70 (0.31)	36 (0.16)	55 (0.24)	75 (0.33)	75 (0.33)	75 (0.33)	108 (0.48)	44 (0.15)
maximum measured lbsF (kN)	75 (0.33)	51 (0.23)	69 (0.31)	79 (0.35)	80 (0.36)	78 (0.35)	115 (0.51)	43 (0.19)
minimum measured lbsF (kN)	55 (0.24)	31 (0.13)	38 (0.17)	43 (0.19)	31 (0.14)	46 (0.20)	76 (0.34)	31 (0.13)
average measured lbsF (kN)	64 (0.28)	40 (0.18)	53 (0.24)	55 (0.24)	57 (0.25)	62 (0.28)	91 (0.40)	37 (0.16)
standard deviation lbsF (kN)	5 (0.02)	4 (0.02)	7 (0.03)	10 (0.04)	12 (0.05)	10 (0.05)	10 (0.05)	4 (0.02)

lbsF pounds force
kN kilonewton

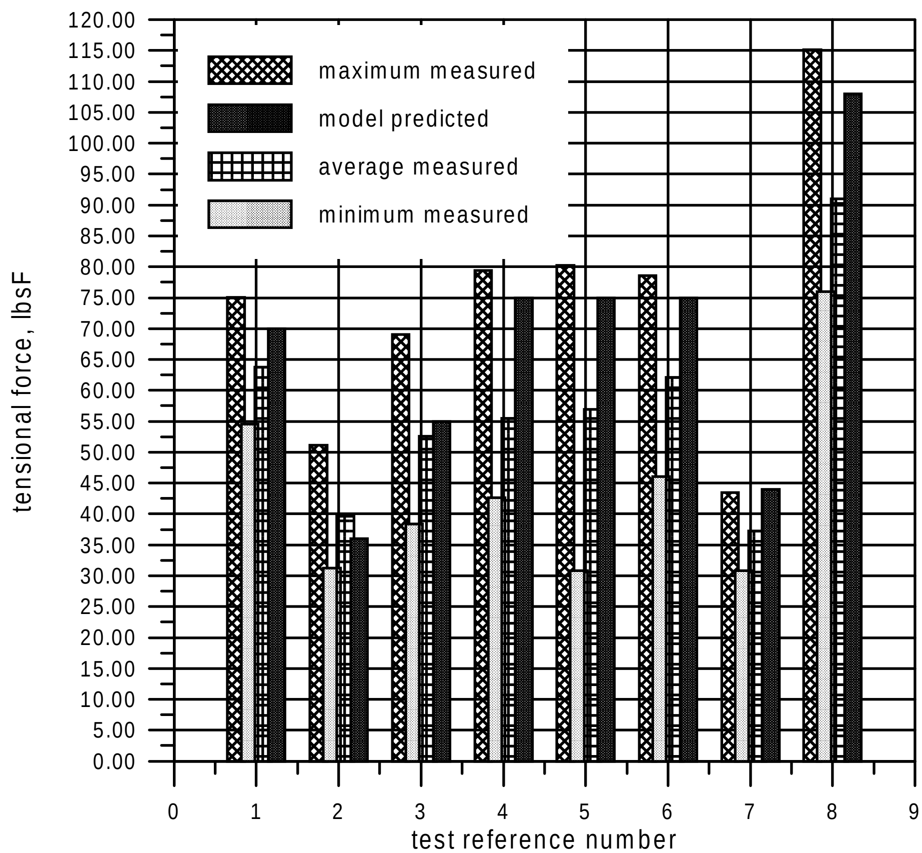

Figure 4. Graph of maximum, minimum, average, and predicted tensional forces exerted during a raise due to variation in contact angle for a constant edge material, rope, and initial load. Source data in Table 2.

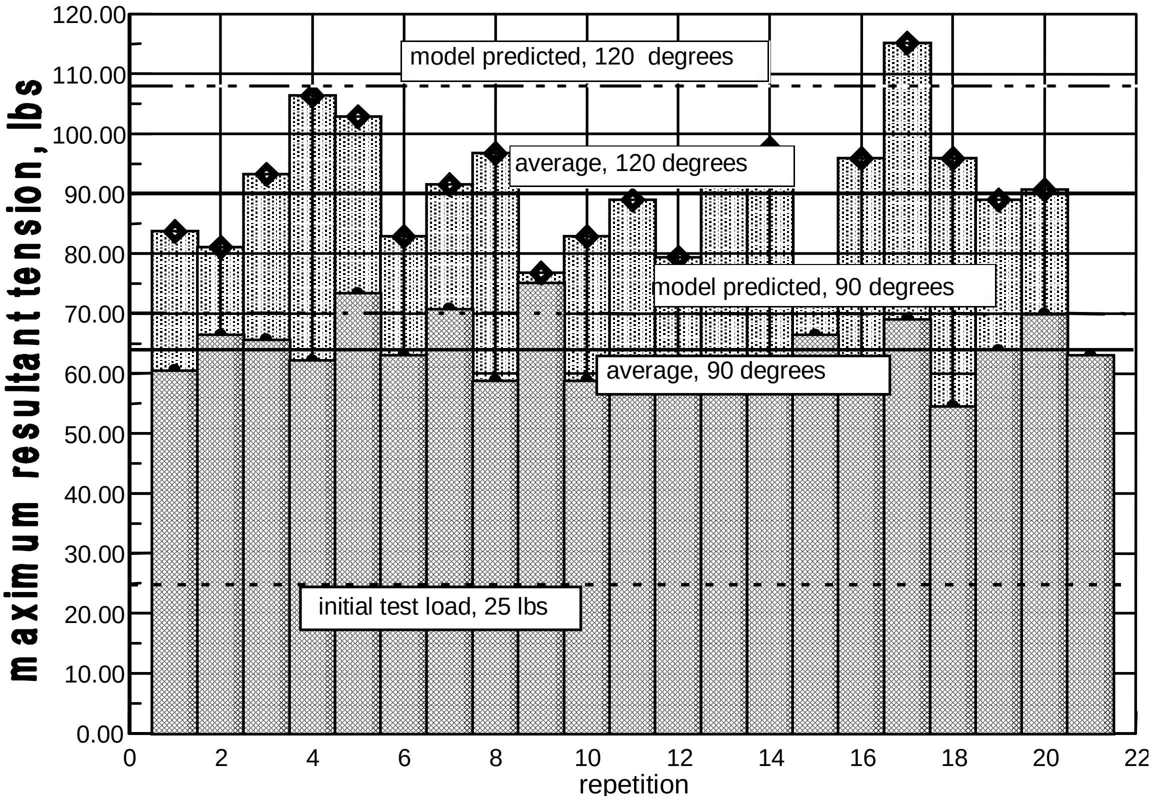

Figure 5. Graph that compares maximum tensional forces exerted during a raise due to variation in contact angle for a constant edge material, rope, and initial load. Model predictions based on a static coefficient of friction of 0.65.

Implications

While this research still continues, some preliminary conclusions can be drawn from the data collected to date. People often assume that the forces and loads at the point of pull in rescue systems are the weight of the litter and litter attendants. Frequently, the design and selection of rescue equipment uses the ratio of minimum breaking strength to load (MBS/L), also called a safety factor. Commonly used MBS/L ratios are 10:1, and 15:1. As an example, the NFPA 1983 (1995 edition) guidelines defines a two-person rescue load as 600 lbsF, and, using a ratio of 15:1, mandates the use of rope materials with a MBS of 9,000 lbsF for a two person load. However, this ratio is only valid for a free-hanging 600-lbsF load on an unknotted rope. In the actual application of a rescue system with friction and angular direction changes, the maximum forces are much higher, and the resulting ratios much lower. Two examples that illustrate the implications of friction and contact angle in rescue systems are presented below.

Example 1). Assume a haul system is built to raise a subject and litter attendant up a 200-foot rock face. Also assume that the profile of the cliff is similar to that in figure 2. The litter and litter attendants are assumed to weigh 450 lbsF (2kN). The rescue team builds a 3:1mechanical advantage (MA), hoping to reduce the force needed to raise the litter assembly to 150 lbsF (0.66 kN). A steel edge protection is placed on the edge at the top. In this rescue, the teams are using 11mm static rope with a new unknotted minimum breaking strength (MBS) of 6,000 lbsF (27kN), and tandem 8mm prussiks, assumed to slip at around 2,400 lbsF. At first glance, the system appears to have a MBS/L of 4:1. During the raise, rescuers find it harder to pull than they expected. If one accounts for friction, the actual maximum tension, just prior to the prusik is 1,499 lbsF (7kN), resulting in a haul force of 500 lbsF (2kN), assuming the use of an ideal 3:1 mechanical advantage. Friction reduces the MBS/L ratio to 4:1 for the main line, and 2:1 for the prusiks slipping. Notice that the haul force using the 3:1 mechanical advantage is actually greater than the rescue load.

Example 2. A rescue in an industrial environment uses a simple raise system built with 12mm rope with an unknotted MBS of 9,000 lbsF, with one point of contact over a rounded steel guardrail. Assuming a rescue load of 600 lbsF, this would develop 1,800 lbsF (8 kN), resulting in an MBS/L ratio of 5:1. Assuming a standard 3:1 MA system is used to raise the load, 600 lbsF would be needed to move the load. Similar to Example 1, this is the same as the primary load.

As shown by the model predictions and bench testing results, reduction of contact friction and/or the contact angle can greatly reduce the maximum tension forces in a system. In Example 2, the addition of a sheet of high-density polyethylene wrapped around the guardrail would result in a maximum tensional force of around 800 lbsF, about 1,000 lbsF less than a system without the polyethylene wrap.

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