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Fall Protection: Minimum Weight Lanyards for Bowhunters

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ABSTRACT

In 1991, there were 2,687,107 bowhunters in the United States following a rich tradition that is thousands of years old. The modern bowhunter is typically equipped with a compound bow, camouflage clothing, dehydrated food and a tree stand. The tree stand, shown in Fig. 1, is mounted 10 to 12 feet above the ground. Here it offers the hunter a large field of view and a stationary position generally outside the animal's field of vision and scent. Bowhunters wear a safety belt for fall protection when climbing to or hunting from a tree stand. This bulletin focuses on the minimum weight design of the safety lanyard.

INTRODUCTION

Safety lanyards are made of rope and are constructed to arrest the fall of a hunter from the tree stand. Assume that a fully equipped hunter of weight P free falls through a height h before reaching the limit of the tether. His potential energy U during free fall is the product Ph and this must be absorbed by the rope to arrest the hunter's motion. As the rope stretches under the falling load, it converts potential energy into strain energy in the rope. The simplest mathematical model of this impact phenomenon assumes that the rope load is proportional to the rope stretch (linear stress-strain behavior). Here, an expression can be derived for the minimum weight rope W that will provide not only quantitative information but also qualitative guidance for the rope designer; thus

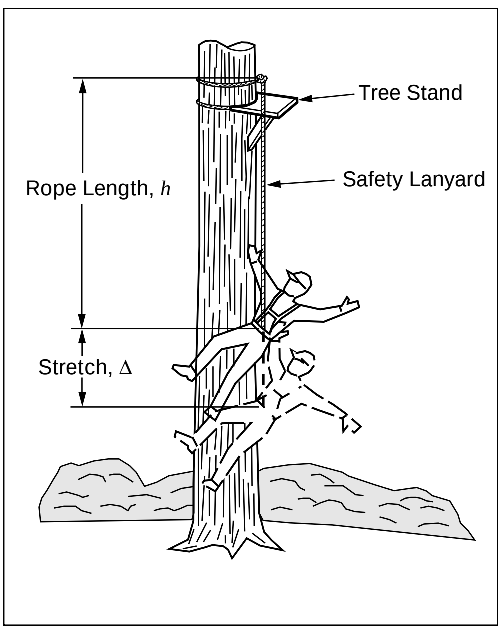

Fig. 1 Tree Stand

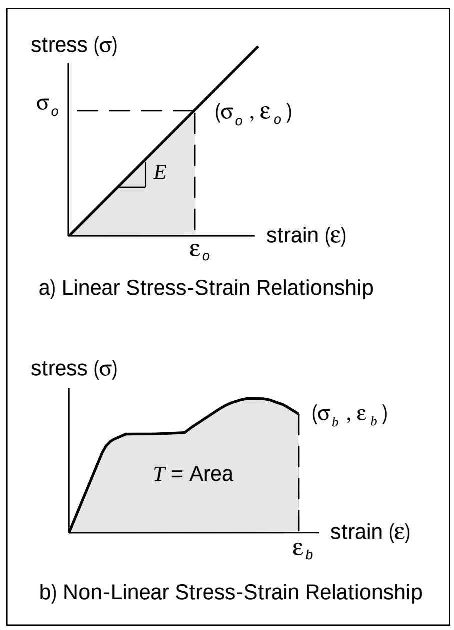

Fig. 2 Lanyard Load-Stretch Behavior

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$$W = 2U\left[\frac{(E/\rho)}{(\sigma_o/\rho)^2} + \frac{1}{(\sigma_o/\rho)}\right] \qquad \text{(Eq.1)}$$

where

E = modulus of elasticity (lbs/in^2)

ρ = weight density (lbs/in^3)

σ_o = maximum achievable stress (lbs/in^2)

DISCUSSION

Input Energy, U: The expression for the rope weight shows that W will be reduced when U is reduced. The following factors will all lead to a reduction in the input energy U:

1. Use the smallest drop height h by selecting the shortest lanyard length compatible with the required movements of the bowhunter in the tree stand.
2. The fall weight P should be minimized by reducing the equipment attached to the hunter.
3. Body friction against the tree uses up energy that may be subtracted from Ph.
4. Lasso friction as the rope moves down the tree uses energy that may be subtracted from Ph.
5. Friction generated in the locking mechanism reduces the input energy U.
6. Body deformations dissipate the input energy.
7. Collisions during the fall absorb energy that will not be transferred to the lanyard.
8. Supportive or evasive maneuvers that absorb energy will reduce U.

Specific Strength, (σ_o/ρ): We observe in Eq. 1 that as the specific strength gets larger, both of the terms in the brackets get smaller which reduces the rope weight W. It should be noted that high strength materials, large σ_o, are not what the rope designer should be looking for. Materials with a high strength to weight ratio, (σ_o/ρ), are required for minimum weight.

The highest possible value for (σ_o/ρ) is the specific tenacity of the material, i.e., the ultimate stress σ_{ult} divided by the weight density ρ, (σ_{ult}/ρ). The largest values of achievable stress σ_o are obtained by minimizing the following parasitic effects*:

1. Rope strength reduction factors for knots, splices, and weaves.
2. Deleterious effects of mechanical devices in contact with the rope.
3. Strength reduction due to environmental effects such as moisture and sunlight.
4. Deterioration of rope strength caused by it's load history, e.g., dragging and securing animals and previous fall arrest scenarios.

Specific Stiffness, (E/ρ): Equation 1 indicates that the rope weight will be reduced when the specific stiffness (E/ρ) is made smaller.

It should be noted that the quantity represented by the square bracket in Eq. 1 is called a merit index; it contains all of the material properties and none of the loading or geometric terms. Candidate materials for minimum weight are evaluated by selecting those with the smallest merit index.

MINIMUM WEIGHT DESIGN

A restrained hunter is shown in Fig. 1 who has free fallen through a height h which is equal to the length of his lanyard. His fall continued until the lanyard stretched Δ and his motion was arrested. At this time his potential energy has been reduced by $P\,(h+\Delta)$ and his kinetic energy is zero. Assume that the lanyard alone absorbs all the potential energy, that its mass is small compared to the mass of the hunter and that it obeys the linear stress-strain relationship shown in Fig. 2a. Then the maximum stored strain energy in the lanyard is given by

$$Ah\left(\frac{\sigma_o^{\,2}}{2E}\right)$$

where A is the lanyard's cross sectional area and the quantity in the parenthesis is the area beneath the stress-strain curve representing the maximum strain energy per unit volume. Applying the law of energy conservation, the potential energy is set equal to the strain energy; thus

$$P(h+\Delta) = Ah\left(\frac{\sigma_o^{\,2}}{2E}\right) \qquad \text{(Eq. 2)}$$

Multiplying both sides of the equation by the weight density ρ and noting that the lanyard weight W may be expressed as $W=Ah\rho$ and that Δ/h is the maximum achievable strain $\varepsilon_o = \Delta/h = \sigma_o/E$, one obtains Eq. 1. Under ideal conditions the absolute minimum weight lanyard per unit length, W/h, is given by

$$W/h = 2P\left[\frac{(E/\rho)}{(\sigma_{ult}/\rho)^2} + \frac{1}{(\sigma_{ult}/\rho)}\right] \qquad \text{(Eq. 3)}$$

Observe that this unit weight is independent of the drop height h and depends only on the hunter's drop weight P and the well defined material properties specific tenacity and specific stiffness.

If the stress-strain behavior of a lanyard material is governed by a non-linear relationship such as shown in Fig. 2b, the maximum strain energy per unit volume that can be absorbed before breaking at a stress σ_b is given by the modulus of toughness T. The total area under the stress-strain curve is equal to T. Setting the potential energy $P(h+\Delta)$ equal to the maximum possible absorbed energy AhT yields

$$W/h = \frac{P(1+\varepsilon_b)}{(T/\rho)} \qquad \text{(Eq. 4)}$$

where ε_b is the breaking strain. No lanyard can weigh less than that predicted by Eq. 4.

* See Andrew C. Sulowski. *Fundamentals of Fall Protection*. (Toronto: International Society for Fall Protection, 1991).