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# APPLICATION OF ANNEALED CABLES FOR VEHICLE ARRESTING BARRIERS

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## ABSTRACT

Transportation and traffic managers have had to deal with increased liability issues regarding containing vehicles during impact with protective barriers. Today's security environment has a heightened need for means of stopping vehicles in controlled manner for security and liability purposes. Using strain energy absorption via annealed steel cables has proven to be a commercial success. Gated vehicle barrier applications using this mechanism range from safely stopping runaway vehicles at railroad crossing in compliance with National Cooperative Highway Research Program (NCHRP) Report 350 to stopping a potential attacker at an industrial plant in compliance with Nuclear Regulation (NUREG) CR-6190. This paper will examine different applications of this mechanism for controlling vehicle impact, analyze the nonlinear interactions at work, and develop operating parameters for using annealed steel wire rope for these applications.

## INTRODUCTION

According to the Federal Highway Administration's website a vehicle or pedestrian is struck by a train every two hours in the US. In 2000 425 people were killed and 1,216 were seriously injured in 3,502 highway-rail grade crossing collisions. In addition to railroad crossing there are bridges and elevated traffic structures in which out of control vehicles are create an increased risk to the structure or other motorists. Most recently there has been security-driven needs to restrict vehicle access at military installations, industrial facilities, and other possible targets vulnerable to hostile and purposeful crashing of gates or other traffic control measures. Annealed steel wire rope or cables can provide significant vehicle arresting capabilities for these applications for either "hard" or "soft" stops through their use in traffic control gates. Since this is a non-standard use of wire rope rules of thumb and other guidelines were not readily available and were developed through experience.

## NOMENCLATURE

Hard stop. Arresting a vehicle in such a manner death or serious injury is likely.

Soft stop. Arresting a vehicle in such a manner death or serious injury is unlikely. NCHRP Report 350 defines these criteria and the testing methods.

$\sigma$: Stress, Mpa (ksi)
$\varepsilon$: Strain, m/m (in/in)
SE: Total strain energy, N-m (lbf-in)
L: Length of wire rope, m (in)
A: Metallic cross section area, $m^2$ ($in^2$)
N: Number of wire ropes engaged in impact
E: Strain energy per unit volume
D: Displacement of the wire ropes, m (in)

Material Considerations.

This paper will examine the use of annealed 304 stainless 6x19 IWRC steel wire rope as an energy absorbing mechanism. Both cables and wire ropes are used in this application, the use of one or the other being driven by economic factors for the equipment manufacturer. The use of one term includes the other for the purpose of this paper. Other materials could also be used in this application. While the specific implementation varies, the general approach is to place the wire rope within a frangible structural member such as aluminum tubing and ensure the wire rope ends are secured when the gate is in its fully down position. During a vehicle impact the wire rope is stretched, the steel is work hardened, the vehicle's kinetic energy is transformed into strain energy, and the vehicle stopped.

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Given the gate holding the annealed wire rope within its structure may be in service for years without ever being struck by a vehicle or otherwise be replaced, the wire rope material had to have sufficient corrosion resistance to be fully capable years later as well as be cost-effective as an expendable item, and highly reliable given its critical application. 304 stainless was selected based on these criteria as well as its ability to absorb considerable strain, failing at over 80% engineering strain at room temperature. [1]

Wire production work-hardens the drawn steel, increasing yield strength from 240 MPa (35 ksi) in the annealed state to 725 MPa (125 ksi) and the tensile strength from 725 MPa (105 ksi) to 1105 MPa (160 ksi.) [2] In typical applications this is advantageous, as it increases its ultimate load as well as the percentage of the tensile strength the wire behave elastically. A common rule of thumb is to specify the service load to be 20% or less than the wire rope's breaking strength. This keeps the stresses within the elastic region, allowing the rope to be used repeatedly without significant stretching. While there is considerable literature available on conventional uses of wire rope, the same is not true of annealed wire rope. Estimating performance on literature values for annealed steel wire can result in significant discrepancies in performance.

Annealing relieves the macro residual stresses due to drawing and manufacturing and reduces the micro residual stresses, but does not eliminate them.[3] This results in materials properties similar to the literature values for the annealed state but not identical. Further, these material properties vary with the effectiveness of the annealing process and directly affect the material's ability to absorb strain energy. Quality control is important in ensuring the wire rope is correctly heat treated.

## Cable mechanics

A wire rope or cable is more mechanically more complex than a single wire strand, the closest approximation available in literature as an annealed item. As the cable takes up the initial load the individual strands tighten against each other as well as the bundles uncoiling slightly, placing the wire strands under slightly varying loads as well as introducing torsion. This affects the reliability of measuring the strain based on length in the elastic region. As the annealed cable is loaded plastically the cables thin and fit more closely together, reducing the structural voids. The combination of thinning strands and the reductions of voids affect the reliability of measuring strain based on diameter change.

These factors create challenges in developing a precise elastic portion of a stress-strain curve. However, what can be counter-intuitive is neither the yield point nor ultimate load is critical for this application compared to the amount of strain exhibited prior to failure. Failure occurs when the wire rope exceeds its ability to absorb further strain energy. Elastic-plastic fracture mechanics [4] can be used to approximate the wire rope behavior, in which a material will absorb strain energy until it reaches its theoretical limit. Integrating the stress-strain curve with respect to strain results in strain energy per unit volume. Symbolically, this can be expressed as:

$$E = \ \sigma\ (force/length^2)\ d\varepsilon\ (length/length)$$
$$\rightarrow force\text{-}length/length^3 \quad \text{(Eqn. 1)}$$

Units are typically N-m/m$^3$ or lbf-in/in$^3$. Integrating numerically over a range of strain provides the energy value per unit volume for a given amount of strain. Once this is done, the total energy can be determined by:

$$SE = L * A * N * E \quad \text{(Eqn. 2)}$$

Where L is the length, A is the metallic cross section area of the wire rope, N is the number of wire ropes of equal length engaged during impact, E is the energy per unit volume previously determined, and SE is Strain Energy. If E is function of strain instead of the numeric integration of the curve, the strain energy can be calculated as a function of strain, which in turn is a function of displacement. Therefore, for a known displacement the total strain energy can be calculated. Typical units for Strain Energy are N-m or lbf-in.

Therefore, while typical wire rope applications base performance on yield strength or tensile (breaking) strength, this application is driven by how much strain energy can be absorbed. Given the elastic region for steel is typically defined by a 0.2% offset curve and 304 stainless steel exhibits up to 80% strain, the area under the elastic portion of the curve is negligible when compared to the plastic portion of the curve.

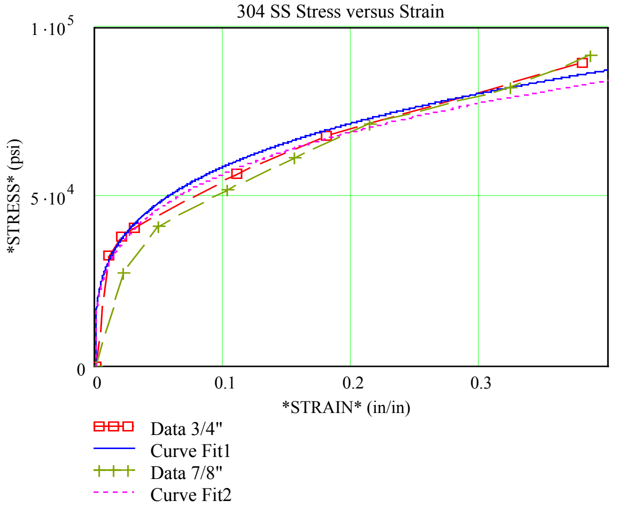

Fig. 1 shows the average results of several pull tests for ½" and

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7/8" nominal diameter 6x19 IWRC annealed wire rope [5]. Each diameter was provided by a different manufacturer. Strain is engineering strain based on cable length. All samples yielded between 45% and 55% strain. Curve fitting the data to a simple exponential curve, the stress can be approximated by a the form $\sigma = K * \varepsilon^n$, where K is the strength coefficient and corresponds to the true stress at $\varepsilon$=1.0 and n is the strain hardening exponent, corresponding to the slope of the log/log plot [1]. In this case the two curves are

$$\sigma_{3/4"} = 1.134E5 * \varepsilon^{0.286} \quad \text{(Eqn. 3a)}$$

$$\sigma_{7/8"} = 1.093 * \varepsilon^{0.286} \quad \text{(Eqn. 3b)}$$

Upon initial inspection the curve geometry conforms favorably to literature true stress-strain curves [1][2]. However, there is a significant difference in the goodness of fit in the plastic region, varying between 20% over the data to 5% under the data. Further, the data represents engineering stress, not true stress, so there should be a noticeable curve instead of a relatively straight line nature in the plastic region in order to satisfy a simple exponential curve fit.

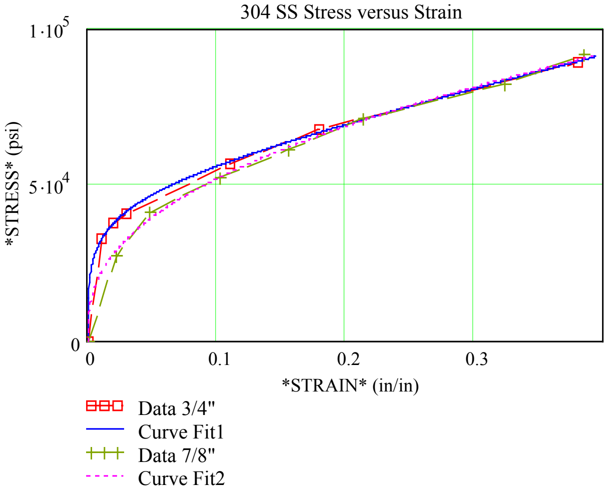

Fig. 2 shows the same data with a higher order curve fit developed through trial and error. Attempts to use geometry factors [4] in describing the stress-strain curve failed to fit. The data indicates failure at significantly less strain than the 82% literature value of the annealed wire, showing the literature data for annealed wire cannot be taken on its face. Also, the data and resultant curve fit for the two different cable diameters show significant differences during initial strain but closely converge as the strain increases. This supports geometry-driven performance differences exist and are reduced as the wire ropes are stretched well into the plastic region, reducing air voids and other discontinuities and more closely behaving as a single wire as strain increases.

The resulting equations are:

$$\sigma_{3/4"} = 2.526E5\ \varepsilon^{0.333} - 2.386E5\ \varepsilon^{0.5} + 1.412E5\ \varepsilon \quad \text{(Eqn. 4a)}$$

$$\sigma_{7/8"} = 7.953E4\ \varepsilon^{0.333} + 4.209E4\ \varepsilon^{0.5} + +1.701E4\ \varepsilon \quad \text{(Eqn. 4b)}$$

These curves are experimental and are not to be considered valid for other materials, diameters, or suppliers. Pull test data must be collected and analyzed appropriately

Another reason for conducting a pull test is to ensure cable fittings are properly installed. An initial crash test prototype failed when the press fit of the swaged fitting pulled free during impact. The fitting must be compressed more than the specifications for standard wire rope require. For example, the unpressed outer diameter of a 7/8" wire rope is 44.5 mm (1.75".) A typical press fit reduces the diameter to 40 mm (1.5625"), but to secure the annealed wire rope sufficient for a pull test to failure the fitting is pressed to 35 mm (1.375".) This was determined by trial and error.

## Impact mechanics

A vehicle impacting an energy absorbing barrier is a conservation of energy problem. If the kinetic energy of the impacting vehicle is less than the barrier's maximum capacity and the structure remains intact, the vehicle is stopped. Strain energy absorbed equals the kinetic energy of the vehicle. Given the relationship between strain and strain energy, the relationship between wire rope displacement and strain energy as well as vehicle kinetic energy and wire rope displacement can be determined. Assume the vehicle travels in a straight line perpendicular to the barrier along its centerline. Energy absorbed or expended in vehicle deformation [8], vehicle dynamics, deformation of the supporting aluminum tubing, and other forms of energy transfer other than the deformation of the wire rope are negligible.

Using trigonometry along the vehicle path, with the undeformed barrier length from the anchor to the centerline being the base of the triangle (a), the travel distance or displacement being the other leg of a right triangle (b), and the hypotenuse being the resultant deformed length (c):

$a$ = base of triangle = $L/2$

$b$ = distance vehicle travel = variable = $x$

$c(x)$ = function of travel = $(a^2 + x^2)^{1/2}$

$\varepsilon(x) = (c(x) - a)/a$ (Eqn. 5)

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These relationships can be refined to account for the vehicle frontage, interlocking gates, or other geometry issues if needed. This approach provides the most conservative assumption with respect to how far the vehicle will travel for a given strain, which is a design issue for the barrier's placement with respect to a key item such as railroad tracks or a no-penetration security zone.

Using data for the ¾" diameter wire rope, Eqn. 4a can be integrated so Eqn. 2 can be rewritten as a function of strain:

$$SE(\varepsilon) = L * A * N * (189450\ \varepsilon^{4/3} - 159066\ \varepsilon^{3/2} + 70600\ \varepsilon^{2}) \quad \text{(Eqn. 6)}$$

Apply this relationship for a 3-rope gate with 15.4 meter wire ropes within the gate structure. Now that the specific barrier configuration has been established, its performance can be predicted. Eqns. 5 and 6 can be combined to determine the strain energy for a given centerline travel. Using test data [6] involving a 2064 kg (4550 lb) pickup truck impacting the barrier at 71 km/h (778 in/sec), the vehicle kinetic energy can be plotted against the strain energy-travel distance relationship to determine the gate's performance.

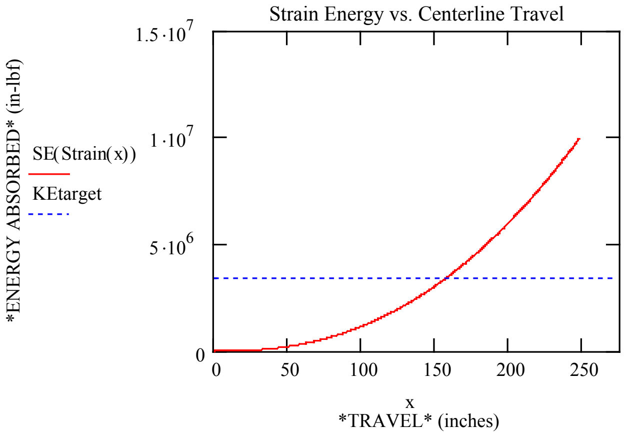

Fig. 3 shows the intersection of the truck kinetic energy to be approximately 3.96 m (156 in.). This corresponds to 15.7% strain using Eqn. 5. Crash test data indicates the truck traveled 3.94 meters, which is less than 1% difference than predicted. This is an exceptionally close match between theory and test. Other crash tests indicate results within 5% - 8% of this numeric model.

Using the stress-strain relations developed in Eqn. 4a combined with Eqn. 5, the stress at a given displacement can be determined. Given stress and area (ignoring area reduction), the force exerted axially to create this stress can be calculated. Since Force = Mass * Acceleration and the mass is known, the resultant acceleration can be calculated. Using the geometry already established, the acceleration on the vehicle with respect to displacement can be expressed as:

$$G(x) = \sin(\tan(x/a))\ [2*N*\sigma(x)*A]/\text{mass}\ * 1/g$$

where (g) is the unit-appropriate term for gravity. The units for G(x) is the number of gravities, which is an industry standard measure for impact barriers and is specified in standards such as NCHRP-350.

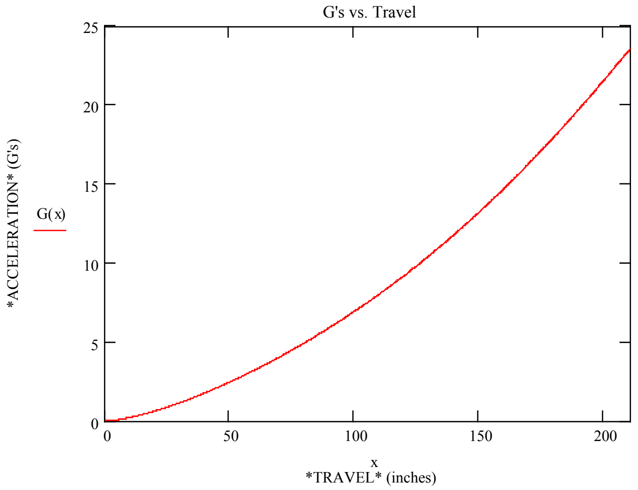

Fig. 4 shows the relationship between distance traveled and the acceleration exerted on the vehicle. Solving the relations for the theoretical stopping distance results in G = 14.7 g's. This compares favorable with the 13.7 g's in the crash test, less than 7% difference. The other crash tests were within 10% of this numeric model.

This numeric model is limited to a centerline impact perpendicular to the barrier. This model may be programmed using a variety of methods such as spreadsheets, calculators, or mathematical solvers. However, other methods such as Finite Element Analysis can perform nonlinear mechanical studies with greater latitude in terms of barrier and impact geometries.

A nonlinear beam element model of this gate was developed using Cosmos/M to verify the previous numeric model as well as provide detailed results. The stress/strain values for the ¾" model were applied to the horizontal beams, representing the cables. The vertical elements are the non-annealed cable lacings to keep the horizontal cables together. A set of nodes in the center of the barrier were displaced 3.96 m (156 in.), with some variance to generally conform to crash test photos of how the wire ropes maintained contact with the front of the truck. For conservativism it was assumed there was little lateral deflection by the annealed cables on the face of the truck, accounting for potential binding during impact.

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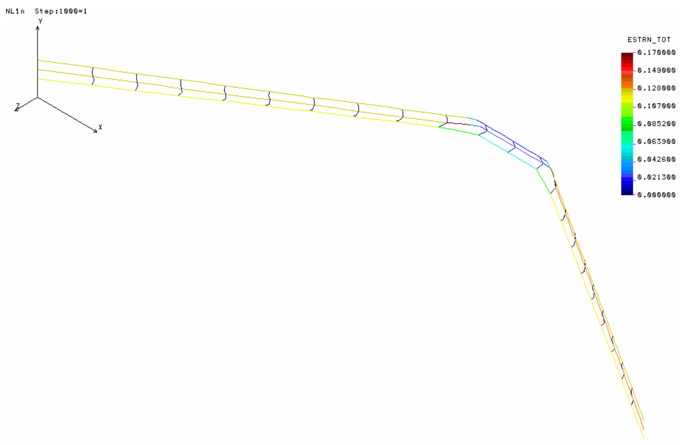

Fig. 5 shows the results of the nonlinear analysis indicates a peak strain of 17% with the typical strain in the barrier being 12-13%. This conforms to the previous numeric results of 15.7% as well as crash test data.

## Design parameters

Given the relationships developed, it is possible to vary the diameter and number of cables engaged for a given barrier length in order to affect the travel distance and acceleration for a given target vehicle mass and velocity. However, in order to determine what a given barrier's capability is it is necessary to develop design parameters.

At the time of this article there are no overall design standards, such as a designated vehicle mass and velocity. Different standards, ranging from NCHRP-350 to Department of the Navy Specification OR-98-09-99 to Nuclear Regulation CR-6190 all have different criteria. Simply stating the barrier complies with a given regulation may not present enough data to assess the barrier in terms of other regulations or other performance parameters. Added to this is the demonstrated variance in annealed wire rope performance. However, since a given structure's strain energy absorption ability is finite it is reasonable to propose guidelines based on this design limitation.

The first parameter proposed is to assume no more than 40% strain. All pull test samples to date have failed above 45% strain, with the majority being above 50% strain. This establishes a maximum strain energy absorption a given system can reasonably be assumed to achieve.

The second parameter is to limit the kinetic energy absorbed to 2/3 of the available strain energy as established with the first parameter. This provides a safety factor of 1.5 in terms of applied kinetic energy to energy absorption capability and allows for the uncertainties inherit in an uncontrolled vehicle impact. This design margin has been accepted by several state departments of transportation. [5]

These parameters assume uniform strain and the expected impact is in the middle third of the annealed wire rope section. Impact in other regions increase the likelihood the shorter section of cable will fail prior to the expected energy is absorbed since binding or significant friction between the wire rope and the vehicle will heavily load the shorter length, which having less material can absorb less kinetic energy. Finite Element Method or Kinematic Modeling techniques can be used to examine other modes of impact if appropriate modeling techniques are used.

## Specific Applications

Vehicle arresting barriers can be divided into those designed to provide a "soft stop," intended to minimize potential injury, and a "hard stop," intended to stop the vehicle within a certain distance with potential injury being secondary. There are currently barriers of both types using annealed cables as the arresting mechanism.

NCHRP-350 is a soft stop standard specifying a series of accelerations for the vehicle and the occupants in order to provide a soft stop, plus the required testing procedures to verify performance. The gated barrier used in this paper was designed to provide NCHRP-350 Level 2 protection for motorists at railroad crossings. It specifies a maximum Ride Down Acceleration is 20.0 g's, a maximum Occupant Impact Velocity of 11 m/sec, and maximum barrier deflection of 6.1 meters. The maximum deflection is to insure the gate can be installed in the railroad easement and still prevent the vehicle from intruding into the locomotive's path.

In addition to the arresting capabilities the gate seats within an endlock when in the down position, preventing motorists from driving around the gate as well as serving as the far side anchor for the wire ropes within the gate structure, addressing intentional violation of a rail road crossing safety mechanism. A series of crash tests as well as third party design reviews using these numerical techniques were submitted to the Federal Highway Commission for technical review. The design and reports were accepted and the design was approved for NHCRP-350 TL-2 applications.

Increasing the diameter of the cable increases the rate of kinetic energy absorption, stopping the vehicle faster with greater acceleration exerted on the vehicle and occupants. While conventional steel cables can hold a greater static load than annealed cables with the same diameter, they absorb less than 10% of the kinetic energy due to being heavily cold-worked from the drawing process. Conventional wire ropes also transmit much higher forces to their anchors for the same

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reason, requiring a strong structure to withstand impact. Several gated barrier designs, previously having conventional steel wire ropes, have been changed to annealed wire ropes to increase the stopping power without changing the gate structure. These are primarily security gates extending over a single access lane into an industrial facility or government site. These are "hard stop" applications, with relatively thick wire rope with respect to its length, and meet requires such as Nuclear Regulation (NUREG) CR-6190. [7]

Annealed steel wire ropes offer many advantages over other mechanisms for vehicle arresting. They are not affected by wet or freezing conditions as disk brakes can be. They require no threat recognition and subsequent activation in order to stop a vehicle since the gate is already in place, making them ideal for security as well as access protection in remote area. Their use is not apparent as they are concealed within the structural members so that a barrier gate and warning gate can be indistinguishable, making it more difficult for a threat force to identify and counter it.

However, there are other concerns that must be addressed for a successful application. The wire ropes must be part of an expendable component as they cannot be re-used. Design issues must include reliable field replacement of expendable components. The wire rope must not be constrained by structures other than their anchors during impact. The effect the barrier will have on the expected range of vehicles must be identified and assessed, to include traffic control measures to influence the vehicle approach direction and speed. Most significantly, the annealed wire rope and its fittings must be tested to ensure accurate data is available for design as well as to ensure the serviceability of the items.

## Conclusion

Annealed wire rope is currently being successfully used in hard and soft stop vehicle arresting barriers. These barriers have proven to be effective in controlling traffic at railway crossings as well as providing enhanced security at vehicular access control points. However, there is little literature available to assist in the design process. Due to potential variances in material properties and mechanical interactions within the cable or wire rope, pull tests should be performed in order to develop accurate performance curves and criteria for the components. As a guideline, the maximum design strain is 40%. The maximum design kinetic energy to be absorbed by the barrier should be no more than 2/3 the strain energy based on 40% strain. The potential effects on the vehicle and occupants must be assessed as part of the design process to ensure these potential outcomes conform to regulatory and liability issues. Additional studies into different design approaches as well as the effects of load rates will potentially increase the use of this arresting mechanism.

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