Technical Notes

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For Professionals Engaged in Post-Tensioning Design *Issue 14 • December 2004*

DESIGN OF PRESTRESSED BARRIER CABLE SYSTEMS

by James D. Rogers[1]

1.0 INTRODUCTION

The selection and design of a vehicle barrier system is an important element in the structural design of every parking garage. Some type of barrier system must be erected at the perimeter of the structure and at the open edges of the ramps to prevent automobiles and pedestrians from falling from the open sides.

The *International Building Code-2003*[2] gives requirements for vehicle impact resistance and states that the barrier system must have anchorage or attachments capable of transmitting the resulting loads to the structure. Since the vehicle impact loads are transmitted to the structure, it is important that the structural designer consider the vehicle barrier system in the overall design of the structure.

One option for vehicle barrier systems is the use of prestressed seven wire steel strand conforming to the Post-Tensioning Institute's *Specification for Seven Wire Steel Strand Barrier Cable Applications*[3]. Steel strands conforming to this specification are capable of restraining the impact load of a moving vehicle and are economical and flexible in meeting the geometric layout of a specific project. Figure 1.1 shows a cost comparison between various types of vehicle barrier systems and illustrates why seven wire steel strand barrier cable systems are a popular choice for garages of all types of construction.

The chart uses the following configurations:

- Barrier cable system consists of 11 cables
- Masonry and cast-in-place spandrels are 42 in. high and built on the slab
- Precast spandrels are 60 in. high and extend over the edge of the slab

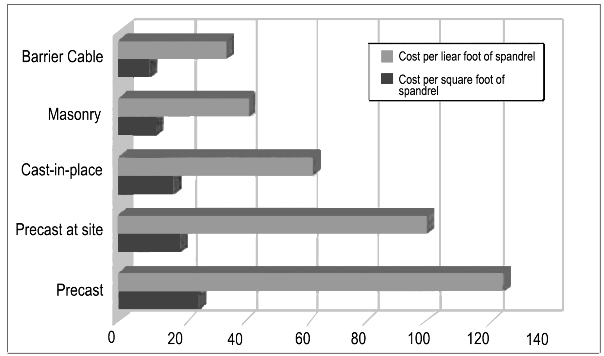

Figure 1.1 – Cost of Exterior Barrier Systems

2.0 BUILDING CODE REQUIREMENTS

IBC outlines requirements for parking garage barrier systems in Section 406.2. This section lists requirements for both pedestrian protection (Section 406.2.3) and for automobile restraint (Section 406.2.4). While the structural designer will typically only be concerned with the barriers that will handle automobile restraint, these vehicle barriers will most likely need to meet the provisions for pedestrian protection as well. Provisions for meeting both requirements are discussed below.

Note that local building code requirements may be more stringent than the IBC requirements, particularly with regards to vehicle impact loads, therefore larger values may need to be used in the design equations that follow.

2.1 Pedestrian protection

Barrier systems for pedestrian protection are required at exterior and interior vertical openings where vehicles are parked or moved, and along open sided walking areas or ramps, when the vertical distance to the ground or surface below exceeds 30 in. [762 mm]. Because of this requirement, most vehicle barrier systems will double as the means for providing protection for pedestrians by meeting the physical requirements of IBC Section 1003.2.12.

This section states that the guard must form a protective barrier not less than 42 in. [1067 mm] high, "measured vertically from the leading edge of the tread or adjacent walking surface." Openings in the guard must be limited such that a 4 in. [102 mm] diameter sphere cannot pass through any opening up to a height of 34 in. [864 mm]. Above a height of 34 in. [864 mm] a sphere of 8 in. [203 mm] cannot pass through the opening(s).

This section also outlines the minimum loading requirements for guards for pedestrian protection, however these loads are not discussed herein since they represent only a small fraction of the load capacity required for vehicle barriers.

2.2 Automobile restraint

IBC Section 406.2.4 requires vehicle barriers not less than 24 in. [607 mm] in height, to be placed at the ends of drive lanes and at the end of parking spaces where the difference in adjacent floor elevation is greater than 12 in. [305 mm].

Vehicle barriers of all types must meet the physical requirements of IBC Section 1607.7, which states that barriers for garages designed for passenger cars are to be designed to resist a single load of 6,000 lbs [26.70 kN] applied horizontally in any direction to the system. For design purposes, the code assumes the load to act at a minimum height of 18 in. [457 mm] above the floor surface on an area not to exceed 1 sq ft [0.9 m^2].

Barriers for garages that accommodate trucks and buses are to be designed in accordance with an approved method that contains provisions for larger vehicles.

Depending on the interpretation of the building official, this may include levels or areas of the garage subject to truck traffic such as delivery areas and loading zones. The traffic patterns in these areas should be carefully considered, as it can be common for these larger delivery trucks to impact barriers when backing up in close quarters.

Another very important (and often overlooked) element of the code is the requirement that the barrier system have anchorages or attachments capable of transmitting the loads (resulting from a vehicle impact) to the structure. Prestressed barrier cable systems are typically anchored to supporting columns or walls in the garage. It is important that the designer calculate the stresses that will result from a vehicle impact to ensure that these connecting elements have the capacity to resist this force. This is particularly important when the connecting column is a short "stub" column (sometimes used on the top level of a parking garage) that most likely will not have the capacity to handle these loads unless additional reinforcing is added.

The following section will present a design method and examples that illustrate a procedure for calculating the forces and deflections that result from a vehicle impact.

3.0 DESIGN CONSIDERATIONS

The primary design consideration is to provide protection by resisting the impact of a vehicle without a failure of the barrier cable system. It is important to recognize that failure of the barrier cable system can occur in several different modes:

- Failure of the anchorage system (either due to the anchorage (or anchorage assembly) itself pulling out of the column, or due to the cable pulling out of the anchorage).
- Failure of the system to limit deflection of the cable on impact to a value that still provides protection.
- Failure of the cable or group of cables to resist the impact without breaking.
- Failure of the connecting column(s) or wall(s)

3.1 Failure of the anchorage system

The connection of the anchoring system to the column(s) or wall(s) is explained in Section 3 of PTI's *Specification for Seven Wire Steel Strand Barrier Cable Applications*[3]. Appropriate material reports and test data should be used to calculate the ultimate pull out and shear strength of <u>all</u> component parts being used.

Failure caused by the cable pulling out of the anchoring device can be avoided by following the material requirements listed in Section 3[3], and by strict enforcement of the installation requirements detailed in Section 5[3]; specifically, all wedge type anchorage devices (the most commonly used in this type of system) **<u>must</u>** be back-stressed to a force equal to 80% of the Minimum Ultimate Tensile Strength (MUTS) of the cable. Barrier cable systems are typically tensioned to a relatively low force that is not adequate to properly seat the wedges and form the mechanical connection that the system relies on. Back-stressing ensures that the wedges are seated and the proper (permanent) connection is made.

Procedures for backstressing are outlined in Section 5 of the Specification[3], and calculations for accommodating the loss of force due to seating loss are discussed later in Section 5.0 herein.

3.2 Limiting deflection

Prestressing steel strand elongates under a load as follows:

$$\Delta = \frac{PL}{AE} \qquad (1)$$

Where: P = the applied load in lbs

L = the length of the strand in inches

A = area of prestressing steel in sq in.

E = modulus of elasticity of the steel

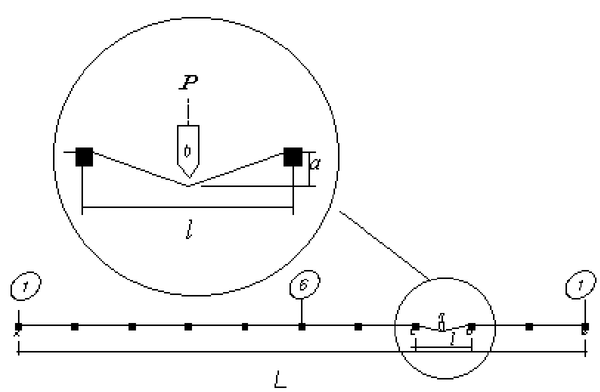

Figure 3.2.1 – Deflection Under a Point Load

Using the model shown in Figure 3.2.1 and ignoring any applied prestressing force, other than what is necessary to remove the slack in the cable, total deflection in a barrier cable strand a can be calculated as

$$a = \left(\frac{Pl^2 L}{8AE} \right)^{1/3} \qquad (2)$$

Using galvanized PC strand with the following properties:

- Cross Sectional Area of Steel (A) = 0.153 in^2
- Modulus of Elasticity (E) = 28,500,000 lbs/in^2

and a barrier cable system with a total length (L) of 200 ft and a column to column span (l) of 20 ft, the deflection of one cable under a 2000 lb load (P) would be:

$$a = \left(\frac{2000 \times 20^2 \times 200}{8 \times 0.153 \times 28{,}500{,}000} \right)^{1/3} = 1.66\,ft.$$

Typically, maximum allowable deflection should be limited to 18 in. in order to prevent the front wheels of an impacting vehicle from traveling over the edge of the slab. However, there are instances where it is important to limit deflection to a lower value. This includes instances when the barrier cable system is placed in front of architectural masonry walls or precast panels that are not specifically designed to handle impact loads. In this case it would be important to limit deflection so that an impacting vehicle would be stopped before it impacted the wall (and sent debris to the ground below). It may also be necessary to limit deflection to the point where a vehicle will not impact cars in opposing stalls or the edge of the slab at adjacent ramps.

When calculated deflection exceeds allowable deflection, the designer has two options:

Increase the pretensioning force in the barrier cable strands (explained in the next section)

or

Add intermediate anchorage devices which shorten the effective length L

Using the previous example and adding intermediate anchorage devices on either side of column line 6 will shorten the effective total length (L) to 100 ft, which reduces deflection (a) to 1.32 ft.

The need for intermediate anchorage devices should be determined by the structural designer and their locations should be clearly shown in the contract documents.

3.3 Calculating the capacity of the barrier cable system

The load on a cable during a vehicle impact is not constant in value, but actually changes with deflection. Therefore the method originally presented in Concrete International[5] termed the "energy method" is the more rational approach to barrier cable design. This method is based on energy principles where the kinetic energy of a moving vehicle is converted to cable force and deflection. Using this method, the designer can accurately calculate both the tension in a cable and the deflection in a cable resulting from the impact of a vehicle of a given mass traveling at a given velocity.

The method consists of two steps; first, determining the tension (T) in a cable upon impact, and then determine the resulting deflection (a). Figure 3.3.1 illustrates a cable of total length L strung between two points A and B. The cable is assumed to be supported by frictionless bearing points at C and D.

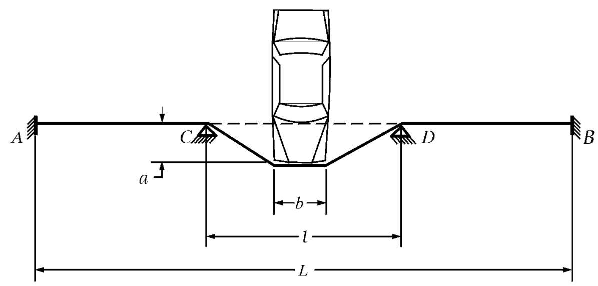

Figure 3.3.1 – Deflection Under Vehicle Impact

This figure represents a typical straight run of barrier cable, anchored only at its end points (A and B). The run may have several spans in its length but the designer should use the longest span l to calculate tension in the cable as follows:

$$T = \sqrt{\left(\frac{EA}{L} \right) \left(\frac{MV^2}{N} \right) + F_e^2} \qquad (3)$$

Where N is the number of cables resisting the impact, V is the velocity of the vehicle in ft/sec, and M is the mass of the vehicle calculated as:

$$M = \frac{VehicleWeight}{g} \qquad (4)$$

The designer starts by choosing an initial value of prestressing force F_e in order to calculate T. The resulting value is then used in the following equation to calculate the deflection of the cable (a) upon impact.

$$a = \sqrt{\left[\left(\frac{T - F_e}{2AE}\right)L + l - b\right]\left[\left(\frac{T - F_e}{2AE}\right)L\right]} \quad (5)$$

If calculated deflection exceeds allowable deflection, the designer can choose a higher value for F_e and recalculate the resulting force T and deflection a, or intermediate anchors can be added (as described in Section 3.2) and then recalculate T and a using the smaller value of L.

As a check against the IBC requirements, the following equation can be used to ensure the system meets the 6000 lb point load requirement.

$$T = \frac{(6000/N) \times l}{4a} \quad (6)$$

Note that a static load of 6,000 lbs is roughly equivalent to a 5,000 lb vehicle impacting the cables at a velocity of 5 mph (14.67 ft/sec).

In either equation, the resulting value of T is the total tension present in <u>each resisting cable</u> upon vehicle impact. This value should be compared with the yield strength of the cables (not the breaking strength) to determine the factor of safety against yielding. If prestressing steel strand conforming to ASTM A416 is used, yield is calculated as 90% of Minimum Ultimate Tensile Strength.

3.4 Column design

The connecting column or wall must be designed to resist the total lateral load that is transmitted to them. This load includes **both** the initial prestressing force that is present in each cable, plus the added force generated by a vehicle impact. This is calculated by using the highest value obtained for T (from Equation 3 or Equation 6) and multiplying it by the number of cables used to resist the impact N, then adding the product of the remaining cables multiplied by the prestressing force (F_e) that has been applied.

Each of the connecting columns should be evaluated to ensure they are able to withstand this total lateral force. This is usually not a controlling factor on a typical column that spans from floor to floor. However, examples in the next section will show that total prestressing force plus the force generated upon impact can be well over 40,000 lbs which can be a factor when using short "stub" columns on the top level of a garage.

Since these short columns do not connect above, they do not have the same capacity as the other "typical" columns. This condition should be carefully evaluated to determine the need for additional reinforcing at the anchoring column(s).

Another factor to consider when using these stub columns is the ability of the intermediate stub columns to resist the same lateral impact load as the rest of the barrier system. In other words, the columns themselves must be able to resist the lateral forces of a vehicle impact without failure. Failure of intermediate stub column(s) upon impact would greatly increase the effective length of l, thereby increasing the deflection (a) to the point of not providing adequate protection. It is particularly important to evaluate this condition when using small steel columns that are simply anchored to the floor.

4.0 PRESTRESSING TO ELIMINATE CABLE SAG

A minimum amount of prestressing force must be applied to the cables to eliminate sagging of the cables under their own weight. PTI's *Specification for Seven Wire Steel Strand Barrier Cable Applications*[3] in Section 5.4 requires all cables to be stressed to a minimum force (F_e) of 2 kips [8.9 kN] for 18 ft [5.5 m] spans in order to limit sagging to an acceptable value.

Excessive sag in the cables is not visually appealing and it may allow the passage of a 4 in. diameter sphere even though cable spacing is less than 4 in. For example, if cable spacing is 3.5 in. but there is 1 in. of sag in the cables, a 4 in. diameter sphere will pass through the opening if enough force is applied to overcome the weight of the cable. Conversely, if cable spacing is 3.5 in. and sag is reduced to 1/8 in., a 4 in. diameter sphere will not pass through unless enough force is applied to start elongating the steel itself.

Cable sag is a function of the weight of the cable itself and the spacing of its supports (l). The following equation[6] is used to calculate sag in barrier cable due to self-weight (w).

$$s_{inches} = \frac{l^2 w}{8F_e} \quad (7)$$

Using the weight of galvanized PC strand, and based on the recommendation of using a prestressing force of 2000 lbs for an 18 ft span, allowable sag calculates to approximately 1/8 in. It is recommended that this ratio (1/8 in. per 18 ft or 0.007 in./ft) be used in calculating the maximum allowable sag in spans longer than 18 ft.

Using this ratio and solving for F_e, the equation for calculating the minimum prestressing force required to reduce sag to an acceptable level is:

$$F_e = \left(\frac{l^2 w}{s/12}\right) / 8 \quad (8)$$

Replacing (s) with the ratio of $0.007l$, the equation becomes:

$$F_e = \left(\frac{l^2 w}{(.007 \times l)/12} \right) / 8 \qquad (9)$$

The chart included as Appendix A of the *Specification for Seven Wire Steel Strand Barrier Cable Applications* lists approximate values for the weight of various types of strand used as barrier cables. Use these values in the above equation to ensure that the prestressing force being used will eliminate sag to an acceptable value. If the force obtained in Equation 9 is higher than the value used in the design equations the designer has two options:

- Use the higher prestressing force obtained in Equation 9 and re-run the design equations, finding a new value for T, a, and for the total load being applied to the anchoring columns.
- Add some type of intermediate spacers or supports to reduce the value of l in Equation 9.

Adding intermediate spacers or supports increases material and labor costs, but may be necessary in garages with very long spans or where it is not desirable to increase the loading on the anchoring columns (or brackets). Note that since these spacers do not provide any lateral resistance they only reduce the value of l as used in Equation 9.

5.0 CALCULATING JACKING FORCE

As previously stated, the relatively low prestressing force (F_e) that is applied to the cable to reduce deflection and eliminate sag is not enough to properly seat the wedges into the anchorage devices typically used with seven wire steel strand barrier cable systems. These wedge type anchorage devices are designed to form a mechanical (not a friction) connection between the cable, the wedge, and the anchor, when the wedges are fully seated. It takes an applied force equivalent to 80% of the Minimum Ultimate Tensile Strength (MUTS) of the cable to fully seat the wedges. When using ½ in. grade 250 PC strand, this force is 30,600 lbs, much higher than the prestressing force (F_e) that is being applied to the cables.

In order to apply the required seating force, the installer must backstress the cable at all anchors to the required 80% of MUTS. This involves stressing each cable to a force equivalent to the calculated final effective force (F_e) plus an additional force needed to compensate for the seating loss that will occur, then removing the stressing jack and using it on the other side of the anchoring assembly to apply the required 80% of MUTS and fully seat the wedges.

The actual technique used for backstressing will depend on the particular job site conditions and is explained in more detail in Section 5.4 of the *Specification for Seven Wire Steel Strand Barrier Cable Applications*.

It is appropriate to assume that the anchorage will experience the full seating loss only upon backstressing. This value is typically 3/8 in. but can vary depending on the particular anchorage system being supplied. The following equation can be used to calculate the jacking force (F_{pj}) that will be required to maintain the required final effective force (F_e) that was determined in the design equations.

$$F_{pj} = F_e + \frac{SeatingLoss \times A \times E}{12 \times L} \qquad (10)$$

Since seating loss can vary according to the type of anchorage system and/or stressing equipment being used, it is typically not appropriate for the designer to specify a required jacking force, but instead should specify the required final effective force (F_e) and then require the barrier cable material supplier to calculate the required jacking force according to materials and equipment being supplied to the project. The supplier should submit this jacking force to the designer as part of the submittal package. The supplier should also supply a stressing equipment calibration chart with the stressing equipment that is being supplied to show the gauge force that corresponds to the required jacking force.

6.0 DESIGN EXAMPLES

6.1 Meeting pedestrian requirements

All of the following design examples will use 11 cables, spaced at 4 in. center to center, with the center of the first cable positioned 3.5 in. above the floor. Using ½ in. cable, this results in a 3.5 in. spacing between each cable, and the height of the center of the top cable is 43.5 in.

Assuming the cables have enough prestressing force applied to them to limit sag and deflection, this will meet the requirements relating to opening sizes and total overall height.

6.2 Number of cables resisting impact

The International Building Code requirements state that the system must resist an impact load located a minimum of 18 in. from the floor and centered on a 1 sq ft area. Given this criteria and the cable spacing cited above, all of the following examples assume that a total of three (3) cables will resist the vehicle impact.

6.3 Example 1:

Total length of cable (L)	=	180 ft
Span length (l)	=	18 ft
Cable		
Grade	=	250 ksi
Yield strength	=	90% MUTS
Cross sectional area (A)	=	0.153 sq in.
Modulus of Elasticity (E)	=	28,500,000
Weight of vehicle	=	5,000 lbs
Width of vehicle	=	6 ft
Impact velocity	=	5 mph

The mass of the vehicle is determined by Equation 4:

$$M = \frac{5000}{32} = 156 \text{ lb-sec}^2/\text{ft}$$

Select an initial pretensioning force (F_e) of 3,000 lbs and calculate the tension upon impact using Equation 3:

$$T = \sqrt{\left(\frac{0.153 \times 28,500,000}{180}\right)\left(\frac{156 \times 7.34^2}{3}\right) + 3,000^2}$$

$$= 8,768 \text{ lbs}$$

Using this pretensioning force, deflection is calculated using Equation 5:

$$a = \sqrt{\left[\frac{(8768 - 3000)180}{2 \times 0.153 \times 28,500,00} + (18 - 6)\right]\frac{(8768 - 3000)180}{2 \times 0.153 \times 28,500,00}}$$

$$= 1.2 \text{ ft}$$

The yield strength of the cable is 34,425 lbs, which results in a factor of safety against yielding in this example of 3.93. Total load transmitted to the end (anchoring) columns would be:

$$(8768 \times 3) + (3000 \times 8) = 50,305 \text{ lbs}$$

Use Equation 6 to check conformance with building code requirements

$$T = \frac{(6000/3) \times 18}{4 \times 1.2} = 7,500 \text{ lbs}$$

Since this result is lower than the value obtained for T using the energy method, no additional steps are required.

To determine the required jacking force, assume the supplier has given a value of 3/8 in. for expected seating loss and use Equation 10 as follows:

$$F_{pj} = 3000 + \frac{0.375 \times 0.153 \times 28,500,000}{12 \times 180} = 3,757 \text{ lbs}$$

6.4 Example 2

All of the above data is the same, except span length (l) is increased to 27 ft and the total length (L) is increased to 270 ft.

Using the same initial prestressing force (F_e) of 3,000 lbs and solving for T:

$$T = \sqrt{\left(\frac{0.153 \times 28,500,000}{270}\right)\left(\frac{156 \times 7.34^2}{3}\right) + 3,000^2}$$

$$= 7,366 \text{ lbs}$$

Using this force, deflection is calculated as

$$a = \sqrt{\left[\frac{(7366 - 3000)\,270}{2 \times 0.153 \times 28,500,00} + (27 - 6)\right]\frac{(7366 - 3000)\,270}{2 \times 0.153 \times 28,500,00}}$$

$$= 1.69 \text{ ft}$$

In order to limit deflection to 1.5 ft, use a higher initial prestressing force of 5,000 lbs and recalculate the resulting tension (T) and deflection (a):

$$T = \sqrt{\left(\frac{0.153 \times 28,500,000}{270}\right)\left(\frac{156 \times 7.34^2}{3}\right) + 5,000^2}$$

$$= 8,382 \text{ lbs}$$

and deflection is

$$a = \sqrt{\left[\frac{(8382 - 5000)\,270}{2 \times 0.153 \times 28,500,00} + (27 - 6)\right]\frac{(8382 - 5000)\,270}{2 \times 0.153 \times 28,500,00}}$$

$$= 1.49 \text{ ft}$$

This limits deflection to 18 in. but total lateral force transmitted to the anchoring columns increases due to the increase in prestressing force applied to the cables.

$$(8382 \times 3) + (5000 \times 8) = 65,146 \text{ lbs}$$

Since the span length is exceeds 18 ft use Equation 9 to calculate the minimum amount of prestressing force required to reduce sag to an acceptable value in the 27 ft span.

$$F_e = \left(\frac{27^2 \times 0.544}{(.007 \times 27)/12}\right)/8 = 3,147 \text{ lbs}$$

Since the force being used (F_e=5,000 lbs) exceeds the force required to reduce sag, no further steps are required.

6.5 Example 3

This example will use the same spans given in Example 1, but will increase the vehicle weight to 17,000 lbs (delivery vehicle on a plaza level):

The mass of the vehicle is

$$M = \frac{17000}{32} = 531$$

Use an initial prestressing force of 3,000 lbs and solve for T:

$$T = \sqrt{\left(\frac{0.153 \times 28,500,000}{180}\right)\left(\frac{531 \times 7.34^2}{3}\right) + 3,000^2}$$

$$= 15,486 \text{ lbs}$$

Using this value the resulting deflection is

$$a = \sqrt{\left[\frac{(15486 - 3000)\,180}{2 \times 0.153 \times 28,500,00} + (18 - 6)\right]\frac{(15486 - 3000)\,180}{2 \times 0.153 \times 28,500,00}}$$

$$= 1.78 \text{ ft}$$

In this example, the prestressing force would have to be increased to 9,000 lbs in order to limit deflection to 1.5 ft, which would increase the total load transmitted to the anchoring columns to 125,000 lbs. Deflection could also be limited to 1.5 ft by adding intermediate anchorages to reduce the total effective length (L) to 90 ft and increasing prestressing force to 4,000 lbs. This would reduce the total load transmitted to the columns to 98,000 lbs, but the use of the shorter cable length decreases the factor safety against yielding to 1.6.

Another option would be to decrease cable spacing in the area of impact and use five cables pretensioned to 4,000 lbs to resist the impact. This would limit deflection to 1.46 ft and would increase the factor of safety to 2.8.

7.0 LIST OF NOTATIONS

A = Cross sectional area of cable, in^2

a = Cable deflection, ft

b = Width of vehicle, ft

E = Modulus of elasticity of cable, lb/in^2

F_e = Final effective pretensioning force, lbs

F_{pj} = Jacking force, lbs

g = Acceleration due to gravity (32.174 ft/sec^2)

L = Total length of cable, anchor to anchor, ft

l = Span of cable between supports, ft

M = Mass of vehicle, $lb\text{-}sec^2/ft$

N = Number of cables resisting impact

P = Applied load, lbs

s = Sag in cable due to self weight, in.

T = Cable tension on impact, lb

V = Velocity of vehicle, ft/sec.

w = Weight of cable per ft, lbs

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1. James D. Rogers is Director of Certification Programs and Construction Technologies at the Post-Tensioning Institute, Phoenix, AZ

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