AN INVESTIGATION OF TENDON STRESS LIMITS FOR PRESTRESSED CONCRETE BRIDGE GIRDERS

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ABSTRACT

With the introduction of the AASHTO LRFD Specifications in 1994, and subsequently many state DOT's design codes, engineers are now required to check fatigue stress ranges in prestressing strands. For instance, PennDOT requires the fatigue check even if the bottom fiber tensile stress is below the one that would crack the concrete. Prior to 1994, engineers were not concerned with the fatigue issue of prestressed concrete beams due to the usual acceptable design assumption of uncracked section which has an infinite life span.

A comprehensive study (264 bridge cases) has been undertaken to determine if the fatigue stress limits of prestressing tendons as prescribed by the current design specifications are applicable, to determine if it is necessary to differentiate the strand patterns for fatigue stress limits, and to clarify between design and serviceability issues. Although the database selected in this study consists predominantly of the prestressed concrete sections typically used in Pennsylvania, the concluding results should be applicable nationwide. The selected bridges include spread box beams, AASHTO type I-beams, and the new PA bulb-tee beams.

INTRODUCTION

Prestressed concrete beams have been and will continue to be the basic components of highway bridge superstructures. In fact, the majority of highway bridges in Pennsylvania use prestressed concrete beams. This type of superstructure system provides the bridge owner with an economical, long-lasting, and high-quality product due primarily to the extensive quality control procedure used during beam casting and the low future maintenance cost associated with a superstructure. Typical prestressed beams used in Pennsylvania bridge construction are box beams, I-beams, or bulb-tee beams, as shown in Figure 1.[1]

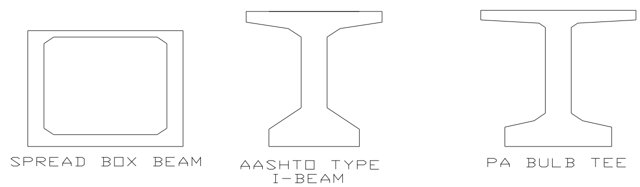

Figure 1. Typical Prestressed Girder Cross Sections

Prior to the introduction of the AASHTO LRFD Specifications in 1994,[2] engineers were not required to check the fatigue stress range limits for prestressed bridge members as fatigue was controlled by a serviceability limit state related to the allowable tensile stress in the bottom flange of the beam and therefore was not a real concern. This design assumption was confirmed by ACI Committee 215 in 1974 which stated that no structural problems attributable to fatigue failures of prestressed concrete beams have been reported in North America.[3] In general, it is believed that deterioration and failure of prestressed concrete beams has more to do with heavy truck traffic, structural aging, and corrosion from severe weathering rather than the fatigue of prestressing strands. Beginning in 1994, engineers have been required to check fatigue stress ranges in prestressing tendons. However, this change deserves further justification as preliminary research indicated that bottom flange tensile stress serviceability limits should not be used to evaluate fatigue life. The paper authored by Wood et al.[4] also states the calculated concrete tensile stress is not a reliable design indicator of strand stress due to live load. It appears AASHTO has chosen a set of conservative guidelines to address the fatigue limit state, as described further in the following.

AASHTO LRFD Bridge Design Specifications[2,5-7] specify that the fatigue stress range in the tendons shall not exceed 18 ksi for straight/debonded strand patterns and 10 ksi for draped strand patterns. These stress range limits are largely based on traditional practices. PennDOT DM-4[8] states that the fatigue stress range in prestressing tendons shall not exceed 10 ksi regardless of the type of strand pattern. This raises the interesting question- Is fatigue stress limit really affected by the strand pattern? Another important point of distinction is that the AASHTO Code allows bottom flange tensile stresses to be doubled of those specified in PennDOT's DM-4 (i.e., $0.190\sqrt{f'_c}$ vs. $0.095\sqrt{f'_c}$), which implies the permission of greater stress range in the tendon. It is also worthy to note that the AASHTO Code[7] states that "*Fatigue of the reinforcement need not be checked for fully prestressed components designed to have extreme fiber tensile stress due to Service III Limit State within the tensile stress limit specified*." However, PennDOT DM-4[8] requires all concrete bridge components except for decks in multi-girder structures to be checked for reinforcement fatigue.

Past design methodologies prior to the release of the AASHTO LRFD Bridge Code never addressed the tendon fatigue issue. Such lack of tendon fatigue analysis was further assured by the fact that fatigue problems had not been encountered in field specimens with decades of service life. The commentary in PennDOT DM-4[7] even states that "*it is believed that fatigue is not of concern*" when addressing tendon stress range, causing many design professionals to question why it has been included in the AASHTO LRFD Codes.[2,5-7] The usual prestressed concrete beam design theory regards the member having an infinite fatigue life as long as the section remains uncracked. Per the AASHTO Code[7], the modulus of rupture for concrete is taken as $0.24\sqrt{f'_c}$. The bottom flange tensile stress limit imposed by PennDOT DM-4[8] is $0.095\sqrt{f'_c}$ which is considerably less than that would crack the beam section. The higher stress limit of $0.19\sqrt{f'_c}$ as permitted by the AASHTO Code[7] is also less than the tension needed to crack the beam. These tensile stress limits vary widely and are significantly lower than that required for cracking as specified in the AASHTO Code.[2,5-7]

OBJECTIVES

Prior to the LRFD design codes, the AASHTO practice to control fatigue was to limit the bottom fiber concrete tensile stresses. Now the code seeks to control fatigue by limiting the stress in the prestressing tendon. While this is a step in the right direction, more research needs to be conducted in order to produce realistic stress range values. The main objective of this study is to determine if the fatigue stress range limits prescribed by the AASHTO Code[7] and PennDOT's DM-4[8] are applicable for beams designed by the current LRFD method. 132 separate cases representing different beam sections and combinations of span lengths and beam spacings were investigated using PennDOT PSLRFD Program[9]. In this study, all cases were limited to interior beams of simple span bridges with no skew. The analysis results were used to calculate the stress ranges developed in the tendons under the fatigue live load vehicle. The calculated stress tendon stress ranges were then compared to the code specified limits.

Another objective is to verify if there is actually a noticeable difference in the tendon stress ranges between straight and draped strand patterns.

SCOPE OF RESEARCH

Fatigue stress ranges in the prestressing tendons were calculated for 24 of the most commonly used prestressed beam sections in Pennsylvania. The database selected includes spread box beams (39-66 in. deep), AASHTO I-beams (63-96 in. deep), and the PA Bulb-Tee Beams (45.25-95.5 in. deep).[1]

For each shape, three different beam spacings (S = 8.25, 10.25, and 12.25 ft.) were considered. As such, slightly different bridge widths were required- 49.375 ft. for S = 8.25 and 10.25 ft. and 45.375 ft. for S = 12.25 ft. The span length for each studied case was maximized for a given beam section and spacing. As a result, the span lengths (L) considered in this study vary from 70 to 165 ft.

Typical barrier width of 1 ft. and 8¼ in. (1.6875 ft.) was used for all superstructures.[10] The following assumptions were also made in this study:

- Haunch thickness: 1½ in. uniform haunch for all beams (i.e., cross slope and corrections for camber not considered).
- Concrete compressive strengths: f'_c = 4 ksi for the deck and 7.5 ksi for the beams.
- Diaphragms (exterior and interior): Located at midpsan.[10]
- Prestressing strands: ½ in. diameter, low relaxation, and f_u = 270 ksi.
- Strand profile: Spread box beams were investigated with straight debonded strands only per the common PennDOT practice. For the AASHTO I-beams and PA Bulb-tee beams, both straight debonded and draped strand patterns were considered. Draped strand patterns assume drape

points are located at 38% of the span length with the only exception of bridge spans less than 80 ft.[8] For spans < 80 ft, the drape point location was placed less than 38% of the span length, since PennDOT's DM-4[8] requires at least 20 ft between drape points.

All beams were loaded with typical dead and live loads transferred from superstructures, and were then designed in compliance with the PennDOT LRFD Criteria.[8] To provide uniformity throughout the research, the following design assumptions consistent with current PennDOT practice were also adopted:

- Concrete deck thicknesses: 8 in. total for 8.25 and 10.25 ft beam spacings, and 9 in. total for 12.25 ft. beam spacing.
- Stay-in-place metal forms: 15 lbs/ft^2.
- Interior/Exterior diaphragms: 10 in. thick.
- Future wearing surface: 30 lbs/ft^2.
- Parapet weight and distribution: 650 lbs/ft with one-half of the load assumed to be carried by an interior beam.
- Rating live loads: PennDOT ML-80 Vehicle (Figure 2) and TK-527 Vehicle (Figure 3).
- Design live loading: PennDOT PHL-93 and P-82 Vehicles (Figure 4)

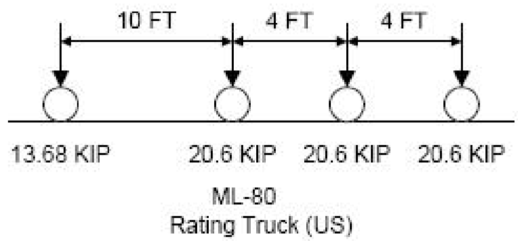

Figure 2. PennDOT ML-80 Rating Vehicle

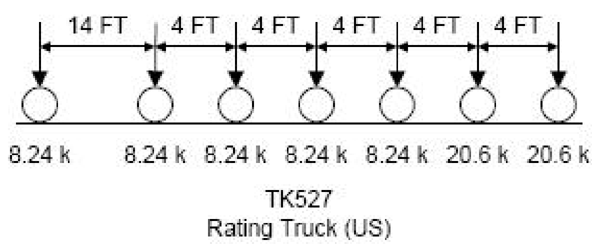

Figure 3. PennDOT TK527 Rating Vehicle

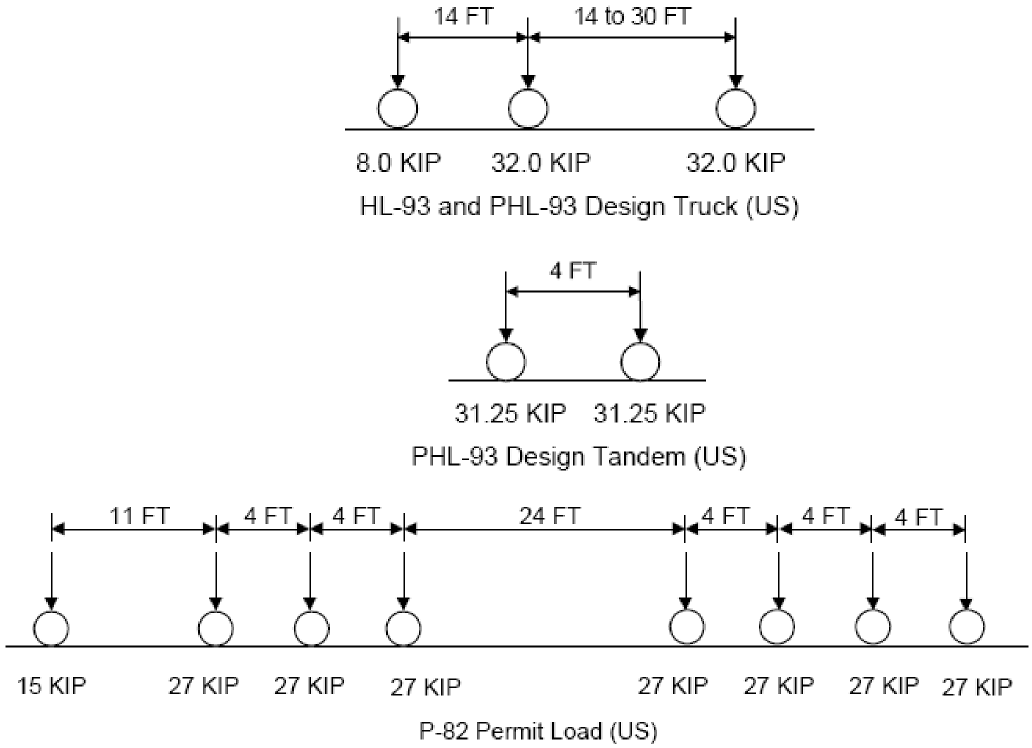

Figure 4. PennDOT Design Vehicles (Note: Superimposed uniform lane load of 0.64 kips/ft for the PHL-93 Design Truck and Tandem not shown)

The PHL-93 live loading considered in this study is similar to HL-93 loading except it increases the tandem load by 25%. In addition to the truck loads, as specified in the design codes[7.8] a lane load of 0.64 kip/ft was considered although it is not shown in the above figures. The concrete deck, beams, exterior diaphragms, and stay-in-place forms were treated as non-composite loads. Composite dead loads consist of parapets and future wearing surface. All live loads are applied to the transformed cross section. Distribution of live loads is based on the live load distribution factors stipulated by the AASHTO/PennDOT Specifications.[7,8]

METHODOLOGY

Fatigue stress range is defined as the stress induced into the beam by the live-load vehicle and is graphically shown in Figure 5 as the difference between points A and B. Point A is located on the compression side of the stress diagram at the level of the prestressing strands (i.e., at C_p location), and indicates the stress due only to dead load. When the live-load vehicle is applied to the beam, it results in a tensile stress causing the stress level in the strands to move to point B. The moment causing this stress change due to the fatigue load plus impact is defined as M_{FL+I}.

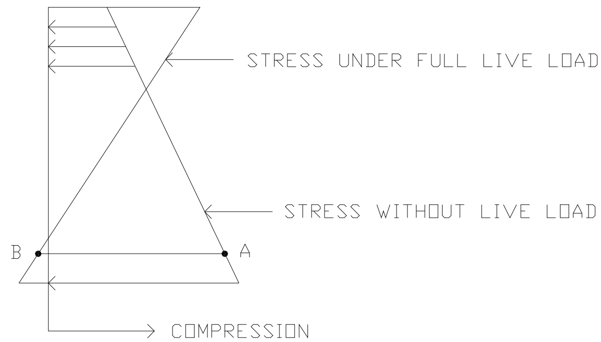

Figure 5. Stress Distribution along the Depth of a Prestressed Concrete Section (Level AB = CG of prestressing tendons; Trapezoidal distribution under dead loads; Triangular distribution under live loading plus dead loads; A to B represents a stress range)

Using basic structural mechanics, the strain in the concrete at the level of the lowest strand can be calculated by:

$$\varepsilon_p = [(M_{FL+I} \cdot C_p)/I_T]/E_c \quad (1)$$

where ε_p = change in concrete strain at the lowest strand due to M_{FL+I}, M_{FL+I} = unfactored moment due to fatigue load (kip-in), C_p = the distance from the neutral axis of transformed section to the lowest level of strands ($C_p = Y_{bt} - 2''$, typically), I_T = moment of inertia of the transformed section (in^4), and E_c = modulus of elasticity of the beam concrete (ksi).

The stress in the strand is then calculated by multiplying the strain in the concrete by E_{ps} (the modulus of elasticity of the prestressing strand = 28,500 ksi). Finally, to get the factored fatigue stress in the prestressing strand the calculated stress must be multiplied by the load factor for the fatigue live-load combination and the Pennsylvania Traffic Factor. The final effective fatigue stress range is computed by:

$$f_{tp} = \mu \cdot PTF \cdot \Delta f_p \quad (2)$$

where μ = load factor (= 0.75, Table D3.4.1.1P-2[8]), PTF = Pennsylvania traffic factor (= 1.2, Table 6.6.1.2.2-1[7]), and Δf_p = unfactored fatigue stress range in the tendon (= $\varepsilon_p \cdot E_{ps}$).

Fatigue stress ranges for all 132 studied cases were calculated using PennDOT PSLRFD Program[9]. Hand calculations for a representative case (Bulb-tee BT 33/95.25 with S = 8.25 ft., L = 155 ft., and debonded strand pattern) were made to verify the computer results (Figure 6).

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 LRFD P/S Concrete Girder Design and Rating, Version 2.2.0.0
Input File: C:\BT-DB\BT95.25\825-155.INP              09/04/2008  14:46:03
---------------------------------------------------------------------------
                   155' SPAN, 8.25' SPACING, BT 33/95.25
---------------------------------------------------------------------------
         SECTION PROPERTIES (COMPOSITE BEAM, TRANSFORMED SECTION)
         --------------------------------------------------------
                          Dist. to Neutral Axis      Section Modulus
Span          Moment of   Bot. of Top of  Top of   Bot. of  Top of  Top of
 No.  Dist.    Inertia     Beam    Beam    Slab    Beam     Beam    Slab
               (in^4)      (in)    (in)    (in)    (in^3)   (in^3)  (in^3)
  1   0.000  2666568.     59.70    35.55    43.05   44663.   75018.   61948.
  1   3.500  2679722.     59.70    35.55    43.05   44663.   75018.   61948.
  1   6.000  2693697.     59.57    35.68    43.18   44987.   75098.   62055.
  1  10.000  2698452.     59.43    35.82    43.32   45329.   75191.   62175.
  1  77.500  2698452.     59.38    35.87    43.37   45446.   75224.   62216.
  1 145.000  2693697.     59.43    35.82    43.32   45329.   75191.   62175.
  1 149.000  2679722.     59.57    35.68    43.18   44987.   75098.   62055.
  1 151.500  2666568.     59.70    35.55    43.05   44663.   75018.   61948.
  1 155.000  2666568.     59.70    35.55    43.05   44663.   75018.   61948.
                           MODULUS OF ELASTICITY
                           ---------------------
          Girder Concrete          Slab       Prestressing       Mild
Span      Final       Initial       Concrete       Steel          Steel
No.       E(c)         E(ci)         E(cs)          E(p)           E(s)
          (ksi)        (ksi)         (ksi)         (ksi)          (ksi)
  1        4990.        4786.         3644.        28500.         29000.
         FATIGUE LIVE LOAD ANALYSIS (UNFACTORED, INCLUDING IMPACT)
         ---------------------------------------------------------
 Span              Maximum Moments          Maximum Shears        Maximum
  No.   Dist.    Positive L  Negative L  Positive L  Negative L  Deflection
        (ft)      (k-ft)  C   (k-ft)  C   (kips)  C   (kips)  C      (in)
   1    0.000         0.0         0.0       42.01        0.00      0.000
        1.000        39.6         0.0       41.71       -0.14      0.007
        7.750       291.3         0.0       39.63       -1.06      0.054
       15.500       547.7         0.0       37.25       -2.17      0.106
       23.250       769.0         0.0       34.87       -3.49      0.156
       31.000       955.3         0.0       32.49       -4.81      0.202
       38.750      1109.2         0.0       30.11       -6.48      0.244
       46.500      1240.1         0.0       27.73       -8.69      0.279
       54.250      1336.0         0.0       25.35      -11.07      0.308
       62.000      1396.9         0.0       22.97      -13.45      0.329
       69.750      1422.8         0.0       20.59      -15.83      0.341
       77.500      1413.7         0.0       18.21      -18.21      0.346

       FATIGUE LL ANALYSIS (REACTIONS INCLUDING IMPACT,DIST FACTORS)
       -------------------------------------------------------------
      Support    Maximum  L   Minimum  L    Maximum  L    Minimum  L
        No.      Reaction C   Reaction C    Rotation C    Rotation C
                  (kips)       (kips)       (radians)    (radians)
        1 R        42.01         0.00      0.000000     -0.000742
        2 L        42.01         0.00      0.000742      0.000000
```

Figure 6. Representative Computer Results (BT 33/95.25 Beam)

From the computer results, the eccentricity of the tendon profile, the transformed section properties, the moment due to the fatigue load combination, and the modulus of elasticity of the beam concrete and prestressing strands are extracted. The effective stress range is then calculated as:

$$f_{tp} = 0.75 \times 1.2 \times 28500 \times [(1422.8 \times 12) \times (59.38 - 2)/2698452] \times (1/4990) = 1.87 \text{ ksi.}$$

As shown in Figure 7, the computer generated fatigue stress range is 1.96 ksi which is slightly higher because the rounded modular ratio (n) of 6 was assumed as opposed to the more exact value of 5.71 (=28500/4990).

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LRFD P/S Concrete Girder Design and Rating, Version 2.2.0.0
    Input File: C:\BT-DB\BT95.25\825-155.INP               09/04/2008  14:46:03
    ---------------------------------------------------------------------------
                       155' SPAN, 8.25' SPACING, BT 33/95.25
                               FATIGUE STRESS RANGE
    ---------------------------------------------------------------------------
                    FATIGUE STRESS RANGE IN PRESTRESSING STEEL
                    ------------------------------------------
                                        Allowable       Actual
                                         Fatigue       Fatigue
                                      Stress Range   Stress Range   * If Code
       Span No.    Distance  Location   f(r,fsr)        f(fsr)        Failure
                     (ft)                 (ksi)         (ksi)
                  1        69.750   MAXIMUM       10.00          1.96
```

Figure 7. Representative Computer Generated Fatigue Stress (BT 33/95.25 Beam)

SUMMARY OF ANALYSIS RESULTS AND RESEARCH FINDINGS

Based on the results from 132 beam cases under PennDOT DM-4[8] criteria (Tables 1-5), the highest fatigue stress in the prestressing strand was found to be 3.23 ksi for the debonded BT33/45.25 beam with S = 12.25 ft and L = 75 ft. This stress is less than one-third of the 10 ksi stress limit permitted by PennDOT. This calculated fatigue stress level indicates that it is not critical to check the fatigue in prestressing strands when the extreme fiber tensile stress is limited to the level set forth by PennDOT.

Table 1 Fatigue Stresses for Spread Box Beams with Debonded Strands

Beam	S (ft)	L (ft)	f_{tp} (ksi)
SR4839	8.25	85	1.55
SR4839	10.25	80	1.62
SR4839	12.25	75	1.61
SR4845	8.25	100	1.54
SR4845	10.25	90	1.57
SR4845	12.25	85	1.58
SR4854	8.25	105	1.35
SR4854	10.25	105	1.44
SR4854	12.25	95	1.46
SR4866	8.25	125	1.25
SR4866	10.25	115	1.30
SR4866	12.25	100	1.25

Table 2 Fatigue Stresses for AASHTO Type I-beams with Debonded Strands

Beam	S (ft)	L (ft)	f_{tp} (ksi)
IB2863	8.25	115	2.51
IB2863	10.25	105	2.86
IB2863	12.25	100	3.08
IB2872	8.25	130	2.48
IB2872	10.25	120	2.78
IB2872	12.25	110	2.92
IB2884	8.25	150	2.28
IB2884	10.25	135	2.60
IB2884	12.25	125	2.76
IB2896	8.25	165	2.13
IB2896	10.25	150	2.45
IB2896	12.25	135	2.55

Table 3 Fatigue Stresses for AASHTO Type I-Beams with Draped Strands

Beam	S (ft)	L (ft)	Max f_{tp} (ksi)	f_{tp} @ Drape Point (ksi)
IB2863	8.25	115	2.50	2.44
IB2863	10.25	110	3.00	2.93
IB2863	12.25	100	3.08	3.02
IB2872	8.25	130	2.47	2.40
IB2872	10.25	120	2.76	2.69
IB2872	12.25	110	2.89	2.82
IB2884	8.25	150	2.28	2.21
IB2884	10.25	135	2.59	2.51
IB2884	12.25	125	2.74	2.67
IB2896	8.25	165	2.12	2.05
IB2896	10.25	150	2.44	2.36
IB2896	12.25	135	2.53	2.46

Table 4 Fatigue Stresses for PA Bulb-tee Beams with Debonded Strands

Beam	S (ft)	L (ft)	f_{tp} (ksi)	Beam	S (ft)	L (ft)	f_{tp} (ksi)
BT3347.25	8.25	100	2.76	BT3347.5	8.25	100	2.75
BT3347.25	10.25	90	3.08	BT3347.5	10.25	90	3.06
BT3347.25	12.25	75	2.86	BT3347.5	12.25	80	3.05
BT3363.25	8.25	120	2.42	BT3363.5	8.25	125	2.49
BT3363.25	10.25	110	2.78	BT3363.5	10.25	115	2.87
BT3363.25	12.25	100	2.87	BT3363.5	12.25	100	2.86
BT3379.25	8.25	140	2.18	BT3379.5	8.25	140	2.17
BT3379.25	10.25	130	2.55	BT3379.5	10.25	130	2.53
BT3379.25	12.25	120	2.69	BT3379.5	12.25	120	2.67
BT3395.25	8.25	155	1.96	BT3395.5	8.25	155	1.95
BT3395.25	10.25	145	2.30	BT3395.5	10.25	145	2.28
BT3395.25	12.25	135	2.45	BT3395.5	12.25	135	2.44
BT3345.25	8.25	90	2.79	BT3345.5	8.25	90	2.77
BT3345.25	10.25	80	3.05	BT3345.5	10.25	85	3.23
BT3345.25	12.25	75	3.19	BT3345.5	12.25	75	3.17
BT3361.25	8.25	115	2.59	BT3361.5	8.25	115	2.57
BT3361.25	10.25	105	2.95	BT3361.5	10.25	105	2.93
BT3361.25	12.25	95	3.03	BT3361.5	12.25	95	3.01
BT3377.25	8.25	140	2.39	BT3377.5	8.25	140	2.38
BT3377.25	10.25	125	2.70	BT3377.5	10.25	125	2.69
BT3377.25	12.25	115	2.84	BT3377.5	12.25	115	2.83
BT3393.25	8.25	150	2.08	BT3393.5	8.25	150	2.07
BT3393.25	10.25	140	2.44	BT3393.5	10.25	140	2.42
BT3393.25	12.25	130	2.60	BT3393.5	12.25	130	2.58

Table 5 Fatigue Stresses for PA Bulb-tee Beams with Draped Strands

Beam	S (ft)	L (ft)	Max f_{tp} (ksi)	f_{tp} @ Drape Pt. (ksi)	Beam	S (ft)	L (ft)	Max f_{tp} (ksi)	f_{tp} @ Drape Pt. (ksi)
BT3347.25	8.25	100	2.75	2.70	BT3347.5	8.25	100	2.74	2.68
BT3347.25	10.25	90	3.07	3.02	BT3347.5	10.25	90	3.05	3.00
BT3347.25	12.25	75	2.85	2.79	BT3347.5	12.25	80	3.04	2.99
BT3363.25	8.25	120	2.41	2.35	BT3363.5	8.25	125	2.49	2.43
BT3363.25	10.25	110	2.77	2.70	BT3363.5	10.25	115	2.86	2.79
BT3363.25	12.25	100	2.86	2.80	BT3363.5	12.25	105	2.98	2.91
BT3379.25	8.25	140	2.17	2.11	BT3379.5	8.25	140	2.16	2.10
BT3379.25	10.25	130	2.53	2.46	BT3379.5	10.25	130	2.52	2.44
BT3379.25	12.25	120	2.68	2.61	BT3379.5	12.25	120	2.66	2.59
BT3395.25	8.25	155	1.94	1.88	BT3395.5	8.25	155	1.93	1.87
BT3395.25	10.25	145	2.28	2.21	BT3395.5	10.25	145	2.27	2.20
BT3395.25	12.25	135	2.44	2.37	BT3395.5	12.25	135	2.42	2.35
BT3345.25	8.25	90	2.78	2.73	BT3345.5	8.25	90	2.76	2.72
BT3345.25	10.25	80	3.03	2.98	BT3345.5	10.25	85	3.22	3.18
BT3345.25	12.25	75	3.18	3.11	BT3345.5	12.25	75	3.16	3.10
BT3361.25	8.25	115	2.59	2.52	BT3361.5	8.25	115	2.57	2.51
BT3361.25	10.25	105	2.95	2.88	BT3361.5	10.25	105	2.93	2.86
BT3361.25	12.25	95	3.02	2.97	BT3361.5	12.25	95	3.00	2.95
BT3377.25	8.25	140	2.38	2.31	BT3377.5	8.25	140	2.37	2.30
BT3377.25	10.25	125	2.68	2.61	BT3377.5	10.25	125	2.66	2.59
BT3377.25	12.25	115	2.82	2.75	BT3377.5	12.25	115	2.81	2.74
BT3393.25	8.25	150	2.07	2.01	BT3393.5	8.25	150	2.06	2.00
BT3393.25	10.25	140	2.43	2.36	BT3393.5	10.25	140	2.42	2.34
BT3393.25	12.25	130	2.59	2.52	BT3393.5	12.25	130	2.57	2.50

In general, for a given beam section fatigue stress level increases with the increase of beam spacing. This is due to a greater fraction of the vehicular loading distributed to the beam. Few inconsistencies were noted due to rounding down of the span length to the nearest 5 ft. Since the resulting fatigue stresses show a consistent pattern, the analysis results are considered generally consistent. Figure 8 demonstrates typical trends of PennDOT calculated fatigue stresses versus beam spacings for PA bulb-tee beams with debonded strands. Draped strands generally show lower stress ranges due to the potential metal-to-metal fretting at holdowns.

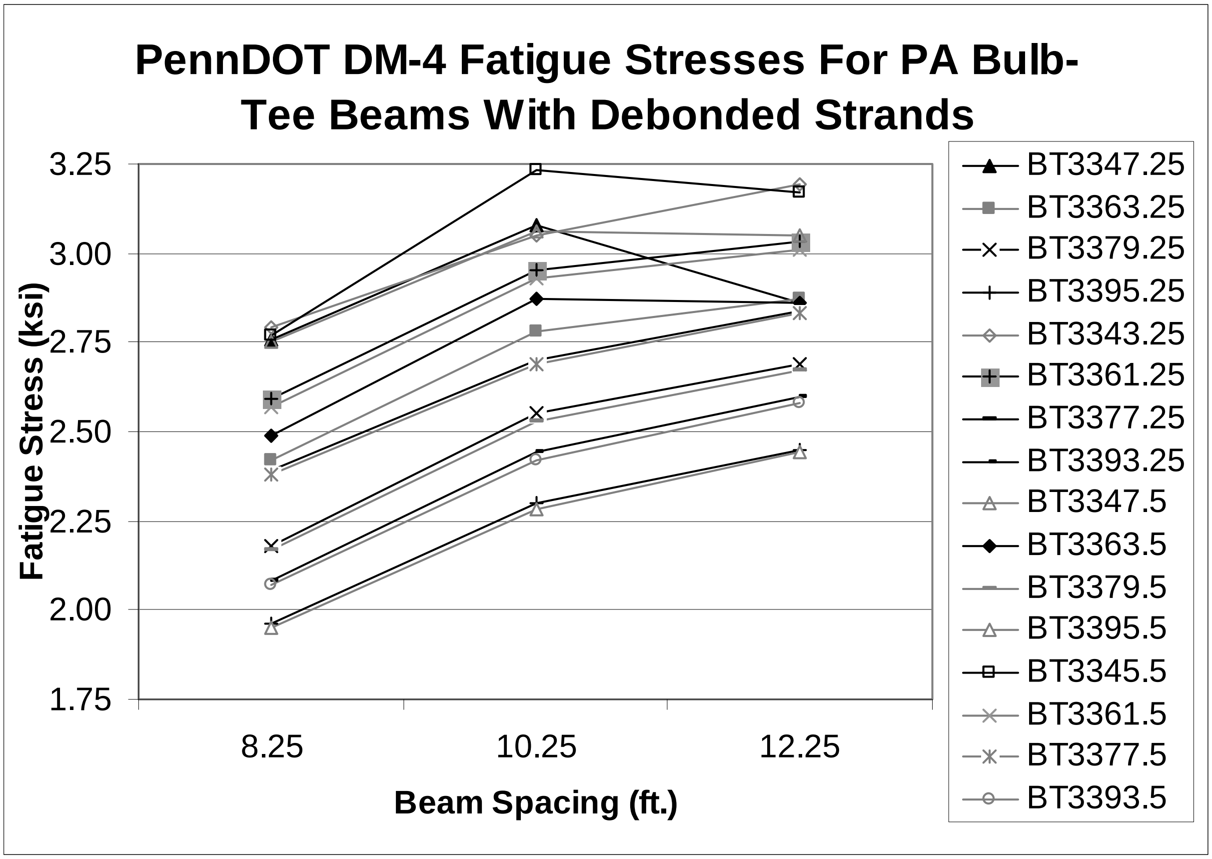

Figure 8 PennDOT DM-4 Fatigue Stresses for PA Bulb-tee Beams with Debonded Strands

CONCLUSIONS AND RECOMMENDATIONS

As shown in this study, the current code-specified stress limits are unattainable for simply supported prestressed concrete beams that are designed based on the LRFD method. The highest computed fatigue stress of 3.23 ksi is less than one third of the prescribed stress limit of 10 ksi. The study results do not reflect PennDOT's conservative stance towards fatigue in prestressing strands. The results of this research also do not support PennDOT's requirement to check the strand for fatigue for simple-span bridges even though the beam has been designed to theoretically not crack. The study results validate PennDOT's statement "*It is believed that fatigue is not a concern*."[7]

Further, the study results do not support AASHTO LRFD provision[7] of a significantly higher stress range for straight (debonded) strands. AASHTO recognizes that the draped strand pattern is more critical since the strands are exposed to metal-to-metal fretting caused by rubbing on tie-downs and increased bending stress due to sharp curvature. As a result, draped strands would be more critical and would experience eighty percent more fatigue stress than straight strands. The study results show that the draped strand pattern is subjected to only 1 to 5 percent higher fatigue stress than the straight strand pattern. The difference is small enough that one stress limit could be prescribed to work for both strand patterns, similar to what PennDOT states in its design manual. Based on this study, it seems there is no need to require different fatigue stress limits between straight and draped strand patterns.

Based on this investigation, fatigue stress in prestressing strands does not present itself as a design concern for simple-span bridges provided that concrete beams are designed in accordance with the extreme fiber tensile stress limits prescribed in the design codes.[7,8]. At the very least, there is no justification for PennDOT to supersede the requirements of AASHTO Section 5.5.3.[5-7]

In terms of further research, the following two areas are suggested:

- Investigate the effects of fatigue on cracked beam sections. It would be interesting to see if the AASHTO and PennDOT fatigue stress limits become relevant using cracked section properties. This would certainly become an applicable situation for structures experiencing heavier truck loading than originally designed for.
- Investigate continuous prestressed concrete beams.

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APPENDIX A - NOTATION

AASHTO	= American Association of State Highway and Transportation Officials
BT	= Bulb tee
C_p	= Distance from N.A. of transformed section to the lowest level of strands

CG	= Center of gravity
DIST	= Distance
DM-4	= Design Manual, Part 4
E_c	= Modulus of elasticity of the beam concrete (ksi)
E_{ps}	= Modulus of elasticity of the prestressing steel (ksi)
f	= Actual fatigue stress range (ksi)
f'_c	= Uniaxial compressive strength of concrete at 28 days (ksi)
f_p	= Final effective fatigue stress range in the tendon (ksi)
f_{sr}, f_r	= Allowable fatigue stress range (ksi)
I_T	= Moment of inertia of the transformed section (in^4)
M_{FL+I}	= Unfactored moment due to the fatigue load plus impact (kip-in)
L	= Span length (ft)
PennDOT	= Pennsylvania Department of Transportation
PTF	= Pennsylvania traffic factor (= 1.2)
S	= Center-to-center spacing of beams (ft)
Y_{bt}	= Vertical distance between the CG and bottom of a beam section (in)
ε_p	= Change in concrete strain at the lowest strand due to M_{FL+I},
μ	= Live load factor for fatigue vehicle (= 0.75)
Δf_p	= Unfactored fatigue stress range in the tendon (ksi)