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CFRP Retrofitting Schemes for Prestressed Concrete Box Beams for Highway Bridges

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Received: 11 December 2016 Accepted: 1 January 2017 Published: 15 January 2017

Abstract

This paper investigates various retrofitting schemes for a prestressed concrete box beam using carbon fiber reinforced polymer (CFRP) sheets with the goal of increasing flexural strength. A simply-supported box beam is studied with a constant uniformly distributed load and three gradually increasing concentrated loads proportional to HS20 truck loading of the Association of State Highway and Transportation Officials (AASHTO). Various retrofitting schemes are considered each with single, double, and triple CFRP sheets, respectively, installed in high compression and tension regions. Cross-sectional nonlinear moment-curvature relations are developed and coupled with a finite-difference solution algorithm to predict load-deflection relations for both retrofitted and non-retrofitted box beams. The study identifies effective CFRP retrofitting schemes that result in a significant increase in the flexural strength of the prestressed concrete box beam.

Index terms— CFRP retrofitting, highway bridges, box beam, prestressed

etrofitting prestressed concrete beams to increase their strength is an evolving area of structural engineering research. Retrofitting with carbon fiber reinforced polymer (CFRP) strips or plates has been used in tensile regions of concrete beams [1][2][3]. CFRP retrofitting material is more advantageous than steel since it is non-corrosive, light-weight, easy to ship, available in practically any length, and easy to install [4][5][6]. It also exhibits superior fatigue resistance, low thermal expansion, and low relaxation [7][8][9]. Using CFRP laminar sheets on various parts of beams with high-strength adhesive epoxy can increase flexural strength and even support any damaged strands without having to demolish the affected areas [10][11][12]. Retrofitting tension regions in beams is of benefit not only to increase strength but also off-set weakness of concrete in tension, and protect prestressing strands from corrosion and vehicle impacts. This paper investigates the effectiveness of using CFRP retrofitting of prestressed concrete box beams in high tensile, compressive, and both tensile and compressive regions. Such retrofitting schemes can provide added strength for highway bridge girders.

Figure **??** shows a simply-supported prestressed concrete box beam used in highway bridges. The beam is subjected to AASHTO-type of loading in addition to the beam self-weight of 0.842 kips/ft. the external loading consists of a uniformly distributed load of 0.64 kips/ft., and concentrated loads 4P, 4P, and P as shown in Figure **??**. The AASHTO loading is obtained if P=8 kips, however, in the present study, the value of P is gradually increased up to collapse condition in the presence of constant uniformly distributed loading. The Type BIII-48 box beam section has two rows of 7-wire ASTM Grade 270 ½ in. diameter strands as shown in Figure **??**.

To demonstrate the effectiveness of CFRP retrofitting, an AASHTO Type BIII-48 box beam cross section [13] is adopted in the present study. Figure **??**a shows the box beam cross section without retrofitting and is used as a reference beam section to determine the effectiveness of various retrofitting schemes. As shown in this figure, the prestressing is achieved with two rows of strands with 23 strands per row. Figures **??**b and 2c show the box beam section retrofitted with a single 40 x 1/16 in. CFRP sheet, in tension and compression regions, respectively. Figure **??**d shows the box beam with single CFRP sheets in both tension and compression regions. Figures **??**e -2g show similar retrofitting schemes with double CFRP sheets while Figures **??**h-2j show those with triple CFRP sheets.ð ??"ð ??" ?? = ð ??"ð ??" ?? ' [2(? ?? /? ?) ? (? ?? /? ?) 2]**(1)**

2 FIGURE 1: PRESTRESSED CONCRETE BOX BEAM WITH AASHTO-TYPE LOADING

The problem addressed in this study is to determine the effectiveness of various retrofitting schemes shown in Figures **??**b through 2j Abstract-This paper investigates various retrofitting schemes for a prestressed concrete box beam using carbon fiber reinforced polymer (CFRP) sheets with the goal of increasing flexural strength. A simply-supported box beam is studied with a constant uniformly distributed load and three gradually increasing concentrated loads proportional to HS20 truck loading of the Association of State Highway and Transportation Officials (AASHTO). Various retrofitting schemes are considered each with single, double, and triple CFRP sheets, respectively, installed in high compression and tension regions. Cross-sectional nonlinear moment-curvature relations are developed and coupled with a finite-difference solution algorithm to predict load-deflection relations for both retrofitted and non-retrofitted box beams. The study identifies effective CFRP retrofitting schemes that result in a significant increase in the flexural strength of the prestressed concrete box beam.

1 Introduction

where ? ?? is the concrete strain, and ? ? is the concrete strain at ultimate compression strength, ð ??"ð ??" ?? ' . The numerical results presented in this paper are based on a ð ??"ð ??" ?? ' value of 5.8 ksi and a concrete modulus of elasticity of 4,383 ksi. Each CFRP sheet used for retrofitting has a thickness of 1/16 in. and a width of 40 in. The Young's modulus of CFRP material is 22,000 ksi and it has an ultimate strength of 260 ksi. is achieved by first formulating the nonlinear momentcurvature relations for the ten cross sections shown in Figure **??** followed by theoretical prediction of the load P versus maximum vertical deflection of the beam.

2 Figure 1: Prestressed concrete box beam with AASHTO-type loading

All moment-curvature relations presented in this paper are derived using 7-wire strands prestressed to a force F equal to 160 kips. In the analysis presented, the effects of keys and fillets on the moment-curvature relations for the cross sections in Figure **??** are considered negligible. This approximation results in only a 0.06% difference in the cross-sectional areas. Figure **??** shows the strain and stress distribution for a simplysupported box beam with CFRP retrofitting at the bottom. In this figure, C c , T ps , and T CFRP are the resultant concrete force, strand force, and CFRP force, respectively. The concrete force is found using:C c = ? ð ??"ð ??" ?? ?? 0 × dA = C c2 -C c1 (**2**)

where:

As seen in Figure **??**c, the concrete strain, ? ?? , can be expressed in terms of the curvature ? and distance ?? from neutral axis (NA):? ?? = ? × ??**(3)**

Substituting Equations 1 and 3 into Equation 2 results in [14]:C c = b 2 × ð ??"ð ??" ?? ? × ? [2 × ? × ?? ? ? ?? 2 0 -(? × ?? ? ?) 2] dx -b 1 × ð ??"ð ??" ?? ? × ? [2 × ? × ?? ? ? ?? 1 0 -(?× ?? ? ?) 2] ????**(4)**

which upon integration gives:C c = b 2 × c 2 2 × ð ??"ð ??" ?? ? × ? ? ? (1 - ? × ?? 2 3 ? ?) -b 1 × c 1 2 × ð ??"ð ??" ?? ? × ? ? ? (1 - ? × ?? 1 3 ? ?)**(5)**

In Figure **??**d, X represents the distance of C c from the NA, and is found using:X × C c =? ð ??"ð ??" ?? ?? 2 0 × b 2 × ?? ???? -? ð ??"ð ??" ?? ?? 1 0 × b 1 × ?? ???? (6)

Using Equations 1, 5, and 6 gives: Moment-curvature relations are developed for seven different loading stages, namely, at zero external moment, zero strain in concrete at the c.g. of the strands, cracking moment, concrete strain reaching 0.001, 0.002, 0.00248, and 0.003 in./in. The linear portion of the moment-curvature relation is developed using elastic stress-strain distribution. The nonlinear portion of the M-? relation is developed by first assuming the top concrete strain and then determining the NA location iteratively until the axial force equilibrium is satisfied. The converged moment and curvature values are then found using the resulting forces and strain distribution. Using this procedure, the M-? curves are developed for the retrofitted cross sections shown in Figures **??**b-2d, 2e-2g, and 2h-2j, respectively. These curves are presented in Figures 4, 5, and 6 including the curve for the non-retrofitted section shown in Figure **??**a. ? f = (0.12 × ?? 0.00008 ??) × 10 -5 (13) ? g = (0.0004M -13.7) × 10 -5 (**??**4)X = c 2 (8 ? ? ? 3 ? × ?? 2 12 ? ? ? 4 ? × ?? 2) -c 1 (8 ? ? ? 3 ? × ?? 1 12 ? ? ? 4 ? × ?? 1)**(7)**? h = M 2.935 × 10 -18**(15)**

? i = (0.035 × ?? 0.0001??) × 10 -5 (16) ? j = (0.0003M -9.5) × 10 -5 (17)

Equations 9 through 17 are obtained using Excel curve-fitting for use in load-deflection analysis based on finite-difference procedure. It is noteworthy that the same moment-curvature given by Equation **??**2is found to be applicable to both of the box sections in Figures **??**d and 2e. Also, in developing Equations 11, 13, and 16, the last point shown on the curves in Figures 4, 5, and 6 for sections 2c, 2f, and 2i, respectively, are excluded. However, these last points were included separately in the solution algorithm.

To predict the load-deflection relations for the prestressed box beam both without and with CFRP retrofitting, an algorithm is formulated based on the nonlinear moment curvature relations coupled with a finite-difference procedure. Figure 7 shows the finitedifference discretization along the longitudinal z axis of the box beam. The node numbers i = 1, 2, ?, N used in the finite-deference formulation are also shown in this figure, with nodes 0 and N+1 as the so-called phantom points. In this study, the segment length h is taken as L/10, where L is the total span of 95 ft. The curvature ? i of the box beam at any node i can be expressed in the following central finite-deference form [15]:? i = (?? 2 ?? ???? 2) i = V i?1 -2V i + V i+1 h 2**(18)**

In this equation, V i is the deflection at any node i. Applying Equation 18 at i = 1, 2, ?, N, the following matrix expression is obtained:[Q] × { V } = h 2 { ? } { V } T = { V 0 , V 2 , V 3 , ?, V N-1 , V N+1 }

The curvature vector is defined by:{ ? } T = { ? 1 , ? 2 , ? 3 , ?, ? N }**(21)**

In Equation **??**9, the following zero deflection boundary conditions are incorporated: V 1 = 0 , V N = 0 © 2017 Global Journals Inc. (US)

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M IV = 4878P -(4.279P × z)+(570w × z)-(w × z 2 /2) for 766 in. ? z ? 1140 in**(22c)**

IV.

4 Solution Algorithm

where [Q] is a N×N coefficient matrix, and {V} is a deflection vector defined by: Year 2017 Based on the values found in { V }, the largest deflection is found to be at node 6 when N = 11 is used in the present study. Using this procedure, the loaddeflection curves for the retrofitted cross sections shown in Figures **??**b-2d, 2e-2g, and 2h-2j are developed and shown in Figures 8-10 including the curve for the nonretrofitted section shown in Figure **??**a.

Table 1 presents a summary of the results based on a rigorous nonlinear analysis of the box beam shown in Figure **??**. In this table, c 2 represents the location of the neutral axis at collapse. The values of the collapse load and the corresponding maximum bending moment are represented by P max and M max , respectively. When nondimensionalized using P max and M max values for the non-retrofitted box beam section 2a, they are entered as p max and m max values in this table. It is seen that the p max values for various retrofitting schemes range from 1.05 to 1.52 showing that the retrofitting scheme using section 2j is the most effective of the ones investigated in this study. The range of m max values is seen to be from 1.03 to 1.35. The second most effective retrofitting scheme corresponds to the section 2g providing a p max value of 1.35.

Figure **??**1 shows the relationships between box beam moment capacity and the CFRP thickness. The upper curve is for retrofitting with CFRP in both tension and compression, and the lower curve is when CFRP is used only in tension. A comparison of the two curves in this figure shows clearly that CFRP retrofitting is significantly more effective when used in both tension and compression regions.

5 Conclusions

The following conclusions are drawn from this study: 1. The use of a 3/16-inch thick CFRP retrofitting layer in both tension and compression regions resulted in the largest increase in the load carrying capacity of the box beam. 2. Retrofitting with CFRP simultaneously in both tension and compression regions is for more effective than retrofitting in just the tensile or the compressive region of the box beam. 3. Retrofitting with CFRP in tension only results in practically the same load carrying capacity of the box beam as that obtained with CFRP in compression only. The nonlinear analysis procedure presented is found to give rapid convergence for the box beam problem studied. [1] [2] [3]

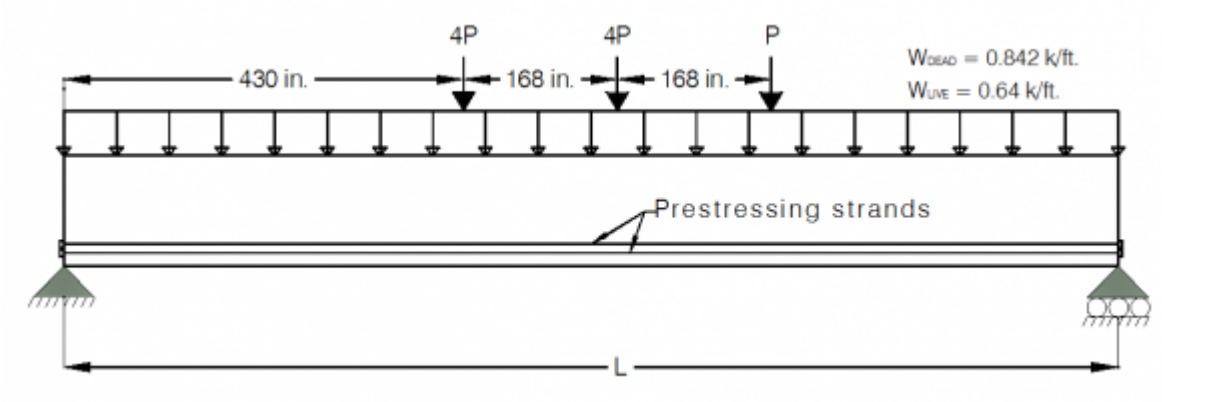

Figure 1:

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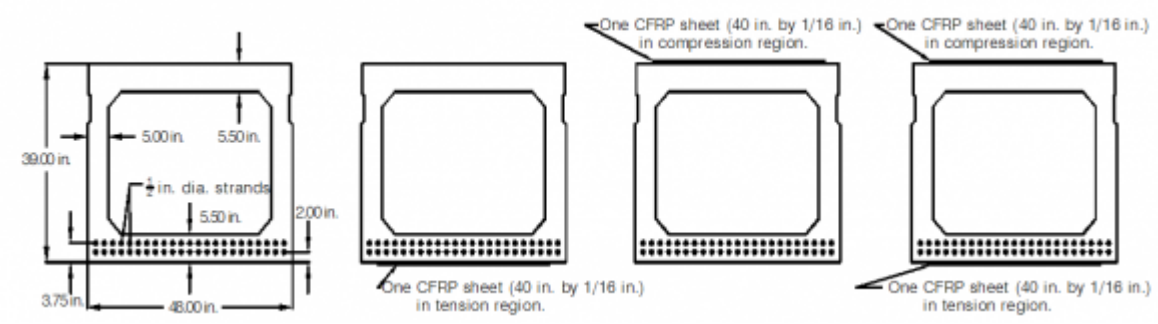

Figure 2:

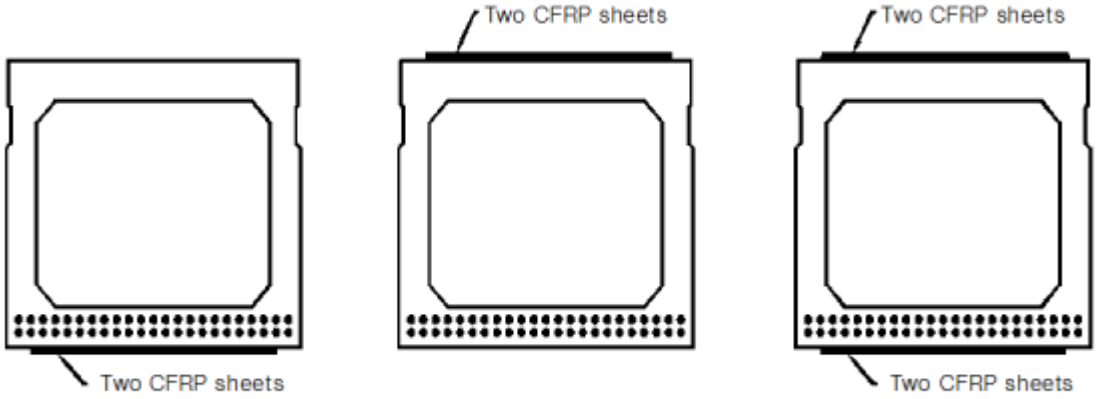

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Figure 3: Figure 2 :Figure 3 :

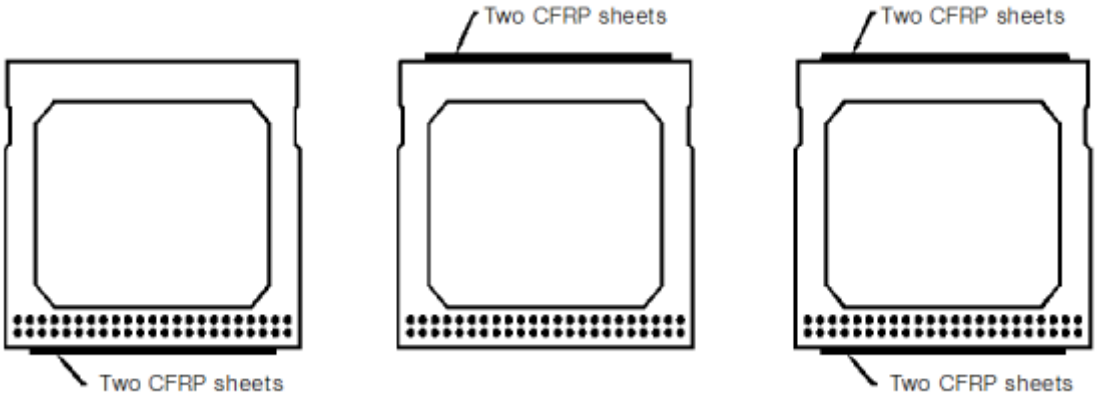

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Figure 4: Figure 4 :

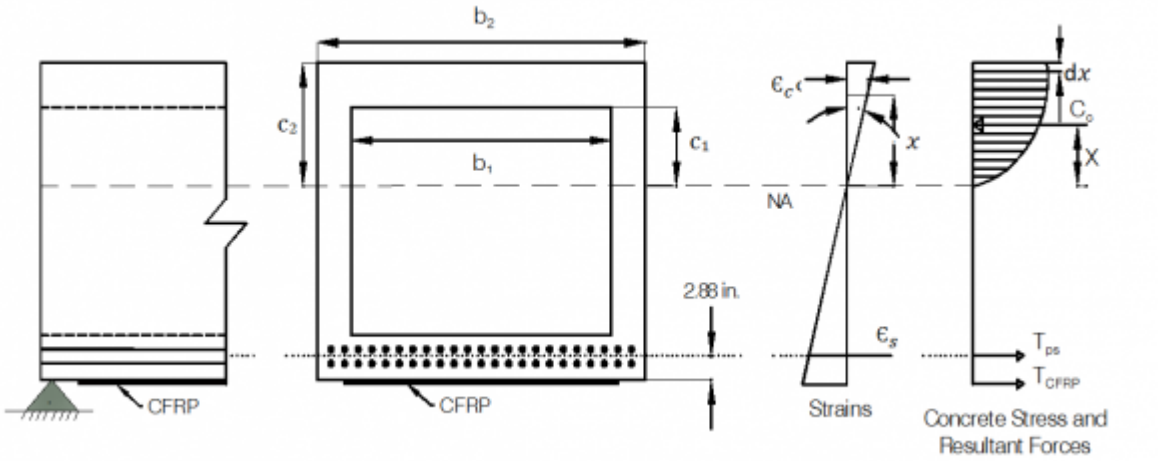

Figure 5:

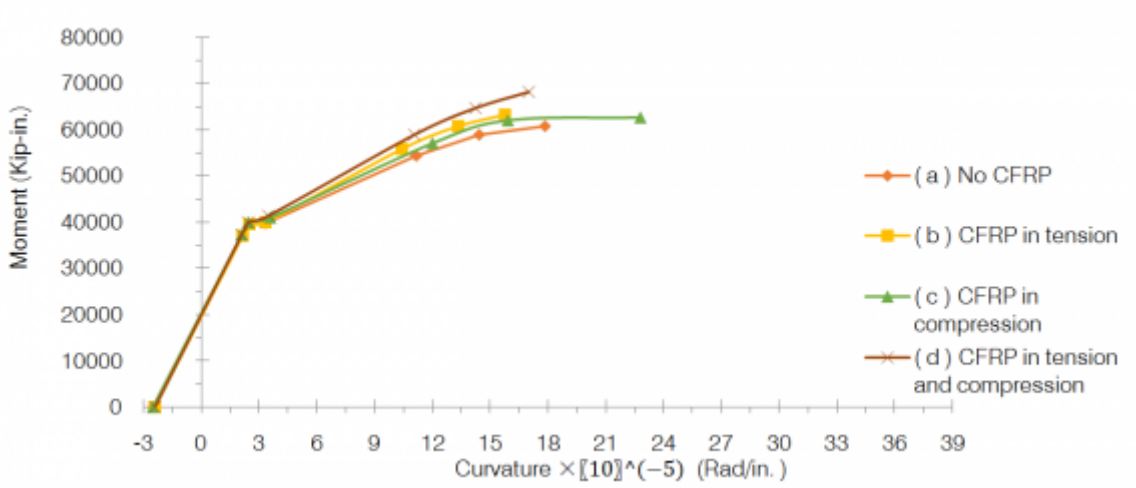

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Figure 6: Figure 5 :

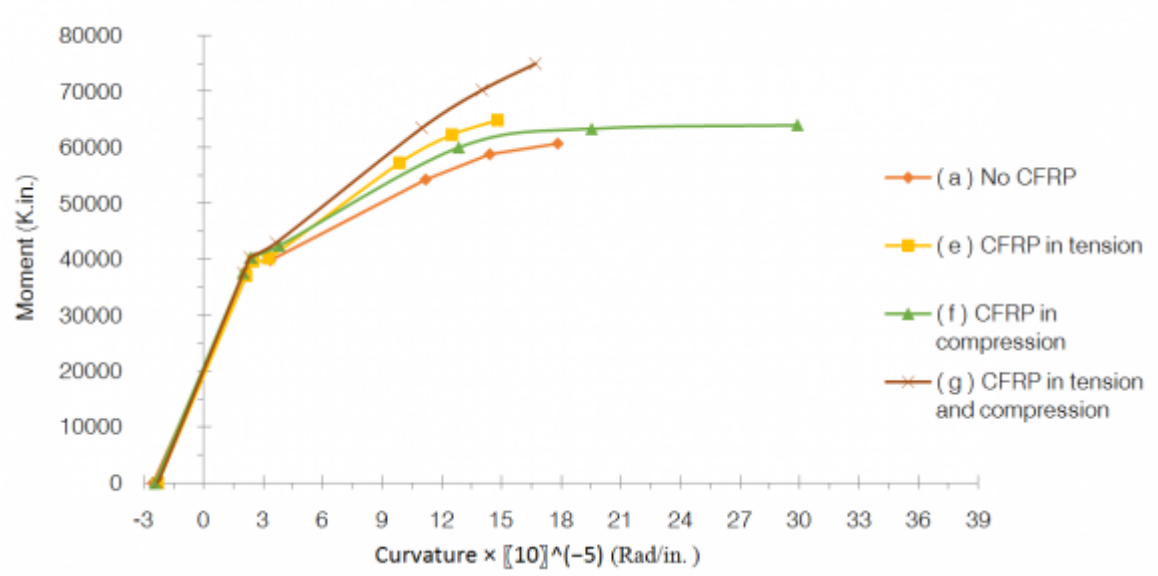

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Figure 7: Figure 6 : 5 (10)

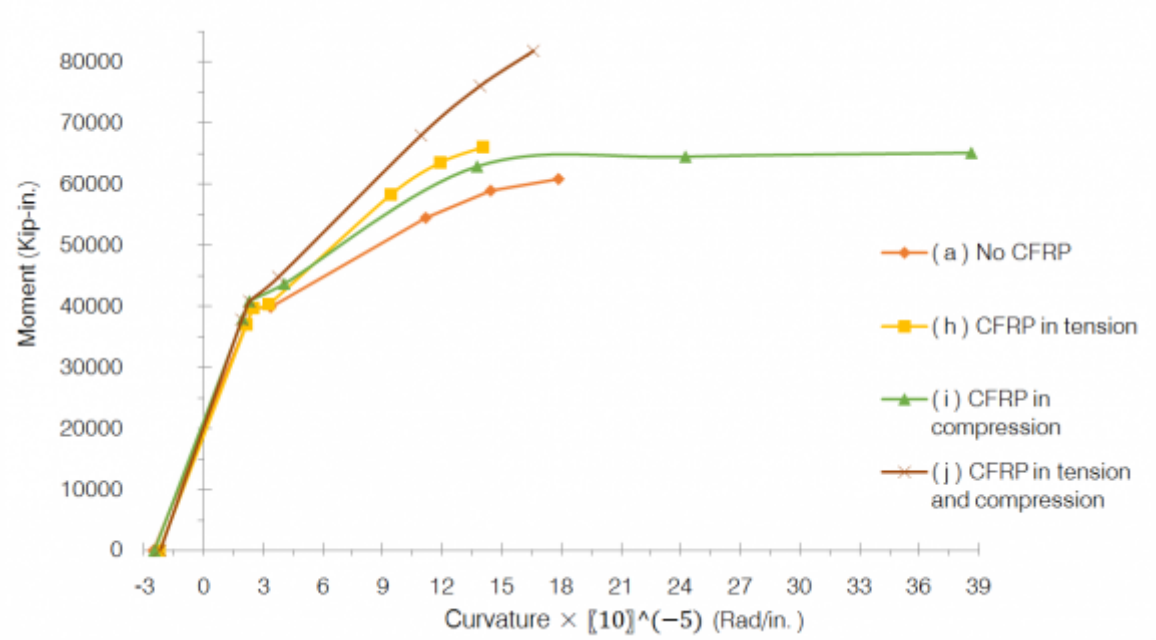

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Figure 8: Figure 7 :

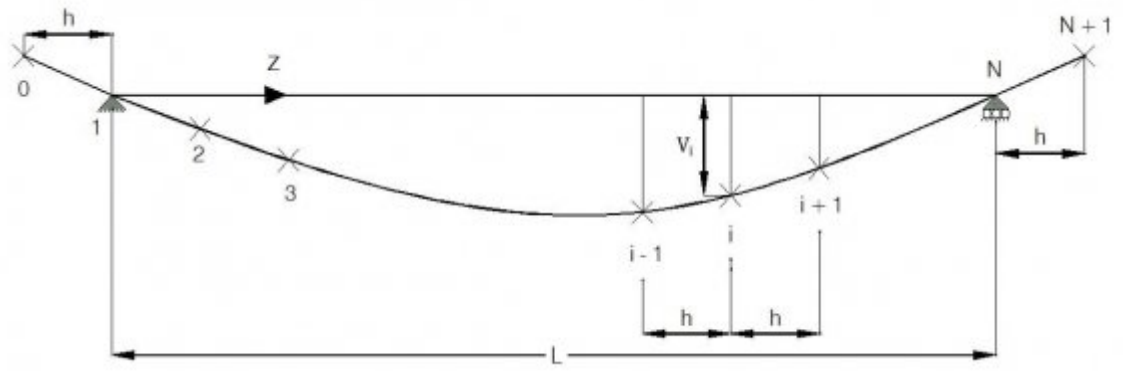

Figure 9: E

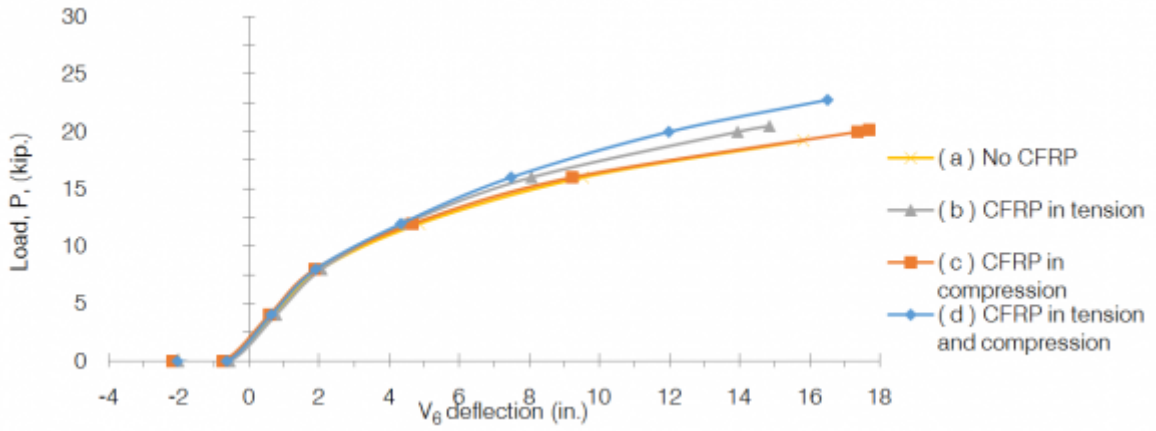

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Figure 10: Figure 8 :

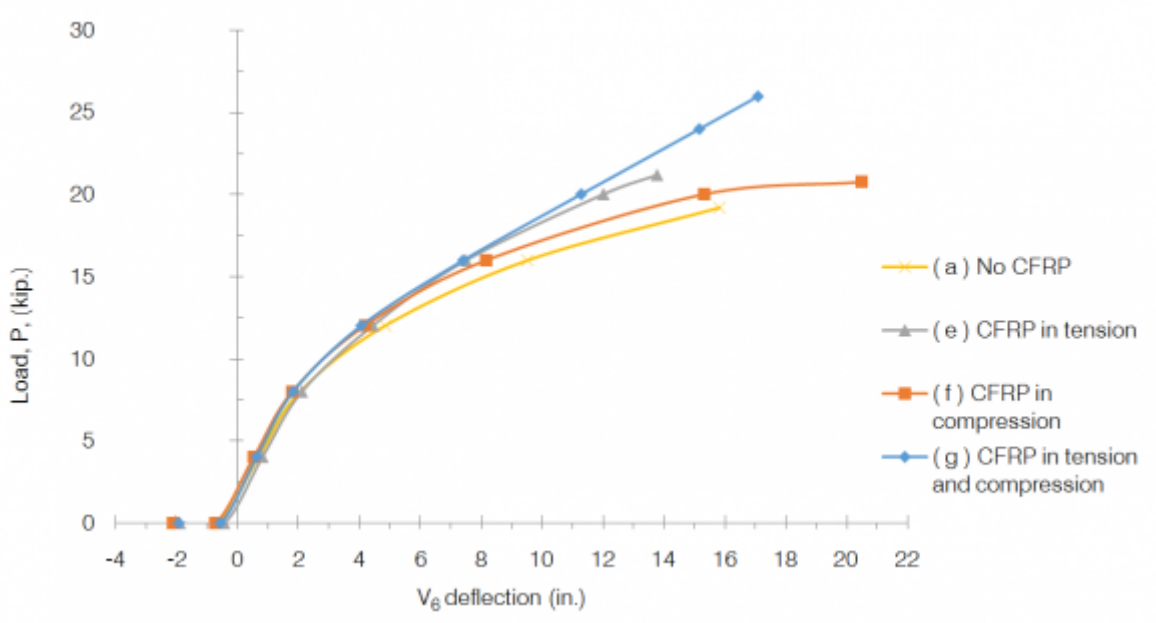

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Figure 11: Figure 9 :

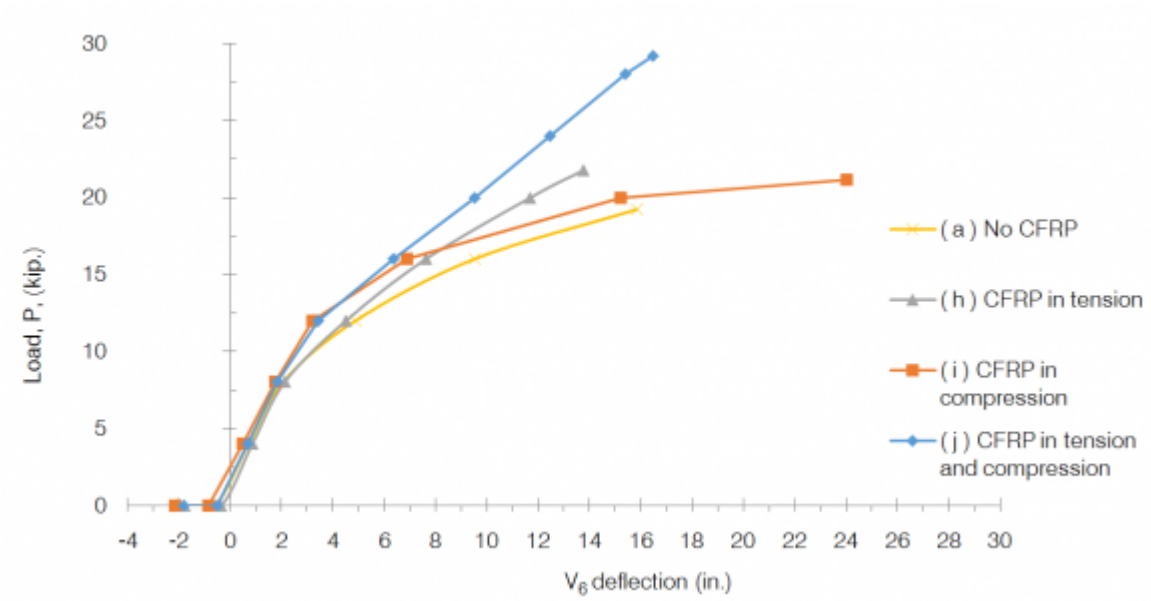

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Figure 12: Figure 10 :Figure 11 :

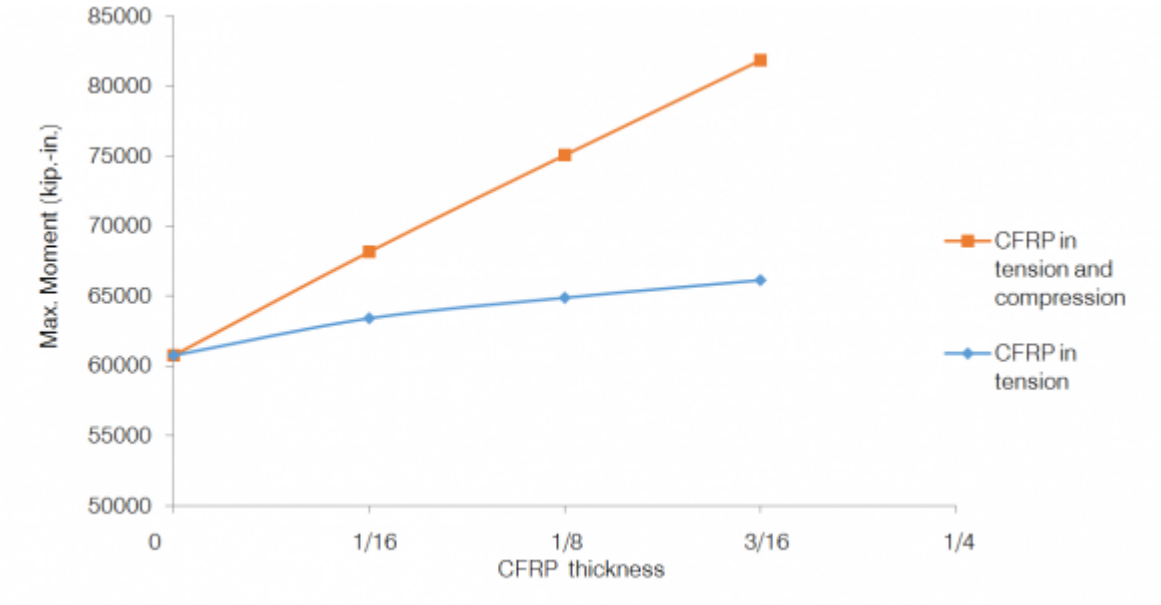

Figure 13:

1

Section (Figure 2)	c 2 (in.)	P max (kips)	p max	M max (kip-in.)	m max
2a	16.81	19.22	1.00	60749	1.00
2b	19.02	20.45	1.06	63364	1.04
2c	13.16	20.12	1.05	62657	1.03
2d	17.64	22.73	1.18	68175	1.12
2e	20.3	21.17	1.10	64876	1.07
2f	10.04	20.78	1.08	64058	1.05
2g	17.94	25.98	1.35	75069	1.23
2h	21.38	21.74	1.13	66098	1.09
2i	7.77	21.27	1.11	65088	1.07
2j	18.12	29.19	1.52	81852	1.45

VI.

Figure 14: Table 1 :

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