Transfer Length of CFRP/CFCC Strands for Double-T Girders

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Presents the results of an experimental investigation addressing the variations in transfer lengths in two types of carbon fiber reinforced polymer (CFRP) prestressing strands. Parameters such as the level of prestress at release, creep, and the rate and method of release of prestress are considered. In all, eight double-T (DT) prestressed girders fabricated with high strength concrete were tested. Four DT girders were prestressed with CFRP Leadline tendons while the other four DT girders were prestressed with carbon fiber composite cable (CFCC) strands. Based on the experimental results, a proposed modification in an available model for predicting the transfer length of CFRP Leadline tendons and CFCC strands is suggested. A comparison of results for the transfer length obtained using the proposed modification with those of others is made. It is shown that the calculated and measured transfer lengths are in close agreement with those obtained by others in the case of Leadline tendons only. It is also noted that the level of release of prestress has no significant effect on transfer length.

Fiber reinforced polymer (FRP) prestressing strands have been used in several structures and bridges[1-3] because of their high strength to weight ratio and noncorrosive characteristics. It is essential to understand the behavior of prestressed concrete members using strands made of carbon fiber reinforced polymers (CFRP).

The transfer length is an important parameter for pretensioned, prestressed concrete structural design, which facilitates determination of the location of the critical section for checking stresses near the ends of members and for checking the flexural and shear strength of the prestressed member. Thus, adequate knowledge of the transfer length for CFRP prestressing strands is absolutely essential so that designers can use it easily for the safe and efficient design of pretensioned, prestressed structural systems.

The transfer length is defined as the length required to transfer the full prestressing force from the pretensioned strands to the concrete. In other words, the transfer length is the length of the bond from the free end of the strand to the point where the prestressing force is fully effective. This is a function of several factors that depend on the properties of both the prestressing tendons and the concrete.

These factors include the size and type of strand, the level of prestress at transfer, the strength of the concrete at transfer, the surface condition of the strand and the method of transfer or release of the prestress. It is well established (Mitchell et al.[4]) that a prestressing steel strand with a rough irregular surface will require a shorter transfer length than one that is clean and smooth. Also, a transfer length for a steel strand will be 6 to 30 percent greater if the release of the strand is sudden rather than gradual.

There are many equations available in the literature, which can be used to determine the transfer length of steel prestressing strands. Most of these equations are empirical and are based primarily on interpretations of experimental results. However, there are only a few equations which deal with transfer lengths of FRP strands.

A brief discussion of the equations and results available in the literature for transfer lengths of steel and FRP strands is presented in the work of Soudki et al.[5] However, for the sake of completeness, some of the equations and results are discussed in the section that follow:

Transfer Length of Steel Strands

Some of the equations for transfer length of steel strands are summarized below:

ACI 318-M98/CSA-A23.3-94 — The provisions of the ACI 318-98 and CSA23.3-94 Codes[6-7] are essentially the same. The equation for transfer length in these codes is as follows:

In U.S. customary units:

$$L_t = {}^{1}\!/_{3}\, f_{pe}\, d_b \text{ in.} \qquad (1a)$$

where

L_t = transfer length of strand
f_{pe} = effective prestress in strand
d_b = nominal diameter of strand

In metric (SI) units:

$$L_t = 0.048\, f_{pe}\, d_b \text{ mm} \qquad (1b)$$

Shahawy et al.,[8] and Buckner[9] suggested that this equation was inadequate and that f_{pe} should be replaced with f_{si}, the initial stress in the strands. Alternatively, Russell and Burns[10] also proposed the same ACI transfer length equation but with a modification by introducing a multiplier factor of (3/2). This revision was found to provide a better correlation with experimental data for small strand diameters.

Model by Cousins, Johnson and Zia — Cousins et al.[11] developed analytical equations for transfer length assuming elastic and plastic bond zones within the transfer length:

$$L_t = 0.5\,(U_t/B) + (f_{se} A_{ps})/(\pi\, d_b\, U_t) \qquad (2)$$

where

U_t = plastic transfer bond stress
f_{se} = effective prestress in the strand
B = bond modulus
A_{ps} = cross-sectional area of the strand

Using the authors'[11] recommended values for steel strands of B = 300 psi/in. (82 x 10^{-3} MPa/mm) and U_t = $6.7\sqrt{f'_c}$ psi ($0.55\sqrt{f'_c}$ MPa), this equation reduces to Eqs. (3a) and (3b) as given below:

In U.S. customary units:

$$L_t = 0.012\sqrt{f'_c} + 0.048\left(A_{ps}/d_b\right)\left(f_{se}/f'_{ci}\right) \text{ in.} \qquad (3a)$$

Table 1. Characteristics of Leadline™ tendons.[23]

Characteristics	Specification
Matrix	Epoxy
Carbon fiber volume fraction (percent)	65
Tensile strength, ksi (kN/mm^2)	328 (2.25)
Young's modulus, ksi (GPa)	21320 (147)
Extension at break (percent)	1.5
Specific gravity	1.6
Relaxation ratio (percent)	2.3
Thermal expansion (1/deg. C)	0.68 x 10^{-6}
Effective cross-sectional area of 8 mm diameter tendon, sq in. (mm^2)	0.071 (46.1), [0.111 (71.8)]*
Guaranteed tensile strength for 8 mm diameter tendon, kips (kN)	23.4 (104), [36.4 (162)]*

*Refers to the tendon of 10 mm diameter.

Table 2. Characteristics of CFCC strands.[18]

Characteristics	1 x 7, 10.5 mm	1 x 7, 12.5 mm
Nominal diameter, in. (mm)	0.41 (10.5)	0.49 (12.5)
Actual diameter, in. (mm)	0.43 (10.9)	0.50 (12.7)
Effective cross-sectional area, sq in. (mm^2)	0.09 (55.7)	0.12 (76)
Linear density, lb/ft (g/m)	0.07 (112)	0.10 (152)
Tensile strength, ksi (kN/mm^2)	331 (2.28)	327 (2.215)
Elongation (percent)	1.7	1.6
Breaking load, kips (kN)	21.6 (96)	31.96 (142)

In metric (SI) units:

$$L_t = 3.36\sqrt{f_c'} + 0.58\left(A_{ps}/d_b\right)\left(f_{se}/f_{ci}'\right) \text{ mm} \quad (3b)$$

where f_c' is the concrete strength and f_{ci}' is the strength of the concrete at strand release (transfer).

Transfer Length of FRP Strands

There are three types of fibers available for FRP prestressing strands. These are aramid fibers, glass fibers and carbon fiber strands. Each of the available FRP prestressing systems[12] and their anchorages are substantially different. As a result, there are significant differences in how load is transferred from the anchor into the FRP tension element and from the tension element to the concrete. Most of the early research on transfer length of FRP strands focused on glass and aramid fibers. More recently, studies[5,19] can be found in the literature regarding the transfer length of carbon fiber strands.

Aramid FRP Strands — Nanni et al.[13] examined the transfer length of braided epoxy-impregnated aramid fiber reinforced polymer tendons. They conducted an experimental study on 25 beams. The specimens, with varying numbers of tendons, were used with tendon sizes varying from $^5/_{16}$ to $^5/_8$ in. (8 to 16 mm). They observed that the transfer lengths ranged from 12 to 20 in. (300 to 500 mm) for low levels of prestress and from 10 to 22 in. (250 to 550 mm) for high levels of prestress. The authors[13] concluded that friction was the predominant bonding mechanism in aramid fibers, and that these fibers showed little slippage when compared to steel strands.

Taerwe and Pallemans[14] conducted a transfer length study using 0.3 and 0.2 in. (7.5 and 5.3 mm) diameter Arapree aramid fiber rods. The 0.3 in. (7.5 mm) diameter rods were coated with Expancel coating to enhance mechanical interlock. The 0.2 in. (5.3 mm) diameter rods had three different surface finishes, namely, sanded, Expancel coating with a smooth surface, and Expancel coating with a sanded surface. The Expancel coating was used to absorb part of the radial compression of the bars. Based on tests on 29 specimens of varying cross sections, a transfer length of 16 times the nominal diameter of Arapree aramid fiber rod was suggested.

Ehsani et al.[12] carried out tests for transfer length on Arapree [0.39 in. (10 mm)], FiBRA [0.41 in. (10.4

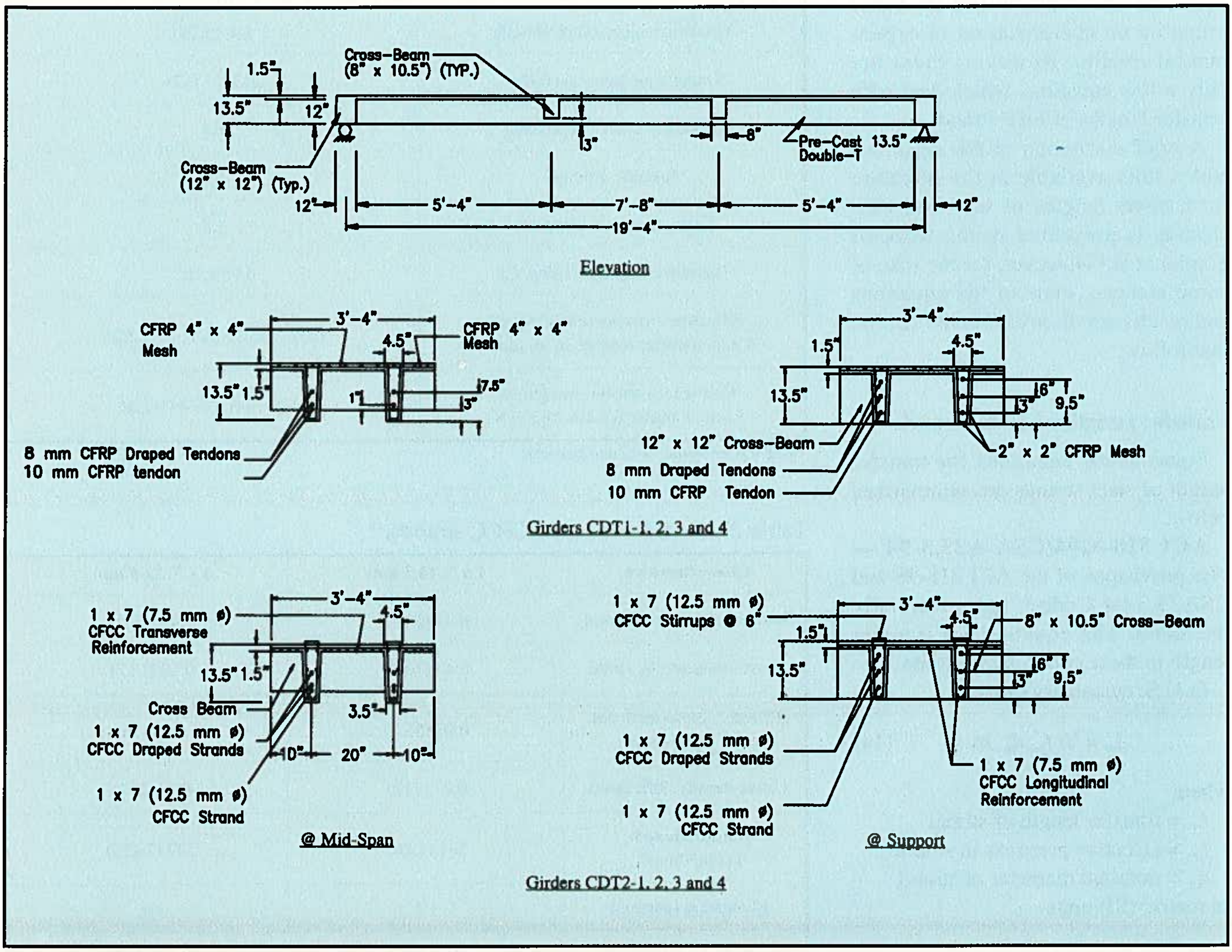

Fig. 1. Details of pretensioned, prestressed concrete DT girders.

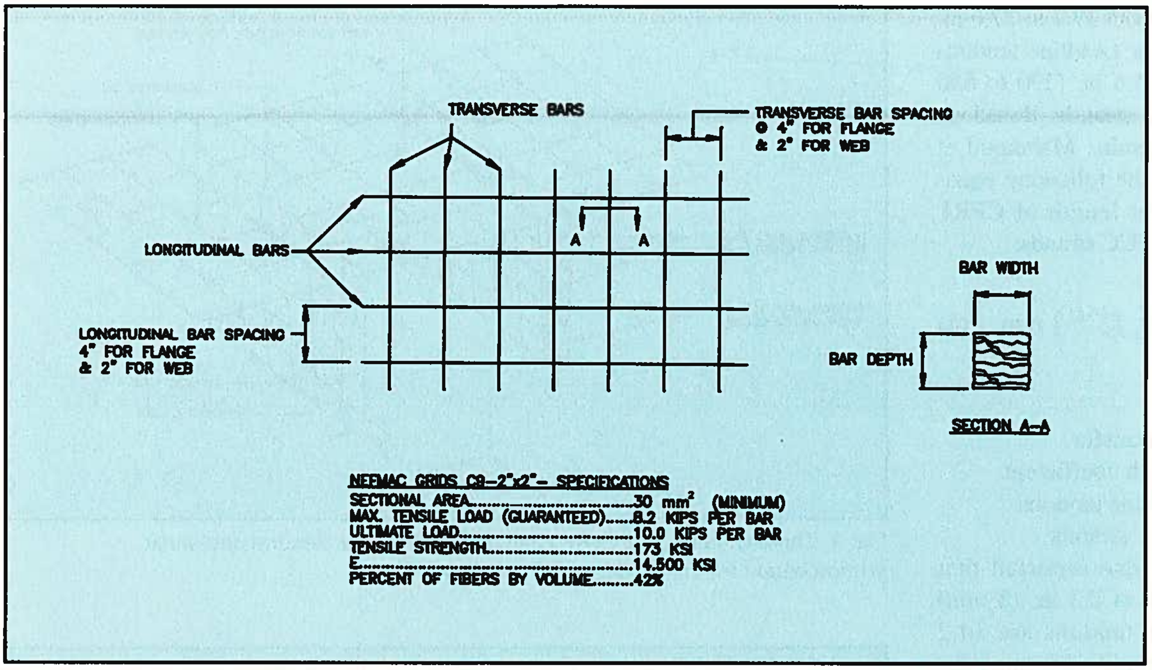

Fig. 2. Typical NEFMAC two-dimensional grid.

mm)] and Technora [0.29 in. (7.4 mm)] tendons. The Arapree tendons were round with a sand-impregnated surface, the FiBRA tendons were braided, and the Technora tendons were deformed with a spiral indentation. The transfer length was found to be 33 bar diameters for FiBRA, 43 bar diameters for Technora, and 50 bar diameters for Arapree. It was also noted that the transfer length for the Arapree tendons was significantly affected by the level of prestress.

Glass FRP Strands — Issa et al.[15] conducted a comparative study of the transfer lengths of fiberglass and steel pretensioned members. Seven specimens pretensioned with two 3/8 in. (9.5 mm) S-2 glass epoxy strands and five specimens pretensioned with a single 1/2 in. (12.7 mm) steel strand were tested. They concluded the transfer lengths to be equal to 28 times the nominal diameter of the strand. Also, they observed that the fiberglass had better bond characteristics than the steel due to better adhesion and interlock at transfer. Additionally, the researchers concluded that the transfer length of fiberglass could be reasonably predicted using the Cousins et al.[11] model with $U_t = 12\sqrt{f'_c}$.

Carbon FRPs — Two types of CFRP strands are most commonly used as prestressing strands. These are CFRP Leadline™ tendons[*] and carbon fiber composite cables (CFCC) strands.[†] A brief discussion on the transfer length results and expressions developed by a few researchers for CFRP Leadline tendons and CFCC strands is presented below.

Abdelrahman[16] reported transfer length data for eight T-beams prestressed with 5/16 in. (8 mm) diameter CFRP Leadline tendons. These transfer lengths are based on a prestress level varying from 40 percent [152 ksi (980 MPa)] to 60 percent [200 ksi (1380 MPa)] of the specified guaranteed strength. The strength of concrete at release was between 5.4 and 7.3 ksi (37 and 50 MPa), and the method of release applied was gradual. The transfer length was found to be 14.2 in. (360 mm) or 46 bar diameters when the stress after release was 138 ksi (950 MPa) and 19.7 in. (500 mm) or 64 bar diameters when the stress after release was 190 ksi (1310 MPa). Thus, the reported results indicate that the transfer length depends on the level of prestress in Leadline tendons after release.

Domenico[17] examined the transfer length and bond characteristics of 20 pretensioned concrete beams prestressed by a seven-wire CFCC[19] strand. The CFCC diameter varied from 1/2 in. to 5/8 in. (12.5 to 15.2 mm). His program considered different concrete covers [2 to 3 in. (50 to 75 mm)], concrete strengths [5.36 to 10 ksi (37 to 70 MPa)], and prestressing levels (50 to 70 percent of guaranteed strength). He found the measured transfer length [varied from 5.5 to 15.7 in. (140 to 400 mm)] to be proportional to the diameter of the CFCC strand and the prestress level.

Ehsani et al.[12] also conducted a transfer length study on Leadline [0.31 in. (8 mm)] tendons and CFCC [0.33 in. (8.3 mm)] strands. They used the same specimens for these tests as they used for tests on Aramid tendons and found the transfer lengths to be equal to 54 times the bar diameter for Leadline tendons and 50 times the bar diameter for CFCC strands.

Most recently, Mahmoud et al.[19] studied the transfer and development lengths of CFRP tendons in 43 pretensioned concrete beams. In their experimental study, 17 beams were pretensioned with Leadline tendons and 26 beams were prestressed with CFCC strands. Three diameters, 7/16, 1/2, and 5/8 in. (10.5, 12.5, and 15.2 mm), were considered for the CFCC strands and 5/16 in. (8 mm) diameter Leadline tendon was used.

The concrete strength at transfer ranged from 3.2 to 5.1 ksi (22 to 35 MPa). The prestressing level varied from 58 to 80 percent of the guaranteed strength. The measured transfer length

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"TM" refers to the trade mark name.

[*] Manufactured by Mitsubishi Chemical Corporation, Japan.

[†] Manufactured by Tokyo Rope, Japan.

was found to vary from 17.7 to 27.6 in. (450 to 700 mm) for Leadline tendons and from 11.4 to 25.6 in. (290 to 650 mm) for the CFCC strands. Based on the experimental results, Mahmoud et al.[19] recommended the following equation for the transfer length of CFRP Leadline tendons/CFCC strands:

$$L_t = \left(f_{pi}\, d_b\right) / \left(\alpha_t\, f_{ci}'^{\,0.67}\right) \text{ mm} \quad (4)$$

where

f_{pi} = prestress at transfer

α_t = transfer length coefficient

α_t = 1.9 for Leadline tendons

α_t = 4.8 for CFCC strands

Abdelrahman[16] also reported that the transfer lengths of 0.3 in. (8 mm) diameter Leadline tendons are 14.2 and 19.7 in. (360 and 500 mm) for prestressing levels of 50 and 70 percent of the guaranteed ultimate strength, respectively. When compared to the above proposed model for Leadline, the results are within 7 to 9 percent of the predicted values using Eq. (4). Soudki et al.[20] reported that the transfer lengths of 0.3 in. (8 mm) diameter Leadline tendons are 25.6 to 28.5 in. (650 and 725 mm) for prestress levels of 50 and 70 percent of the guaranteed strength, respectively. These reported values are 20 percent higher than those predicted using the proposed model in Eq. (4).

TEST PROGRAM

The major purpose of this experimental program was to determine the transfer length of CFRP Leadline tendons and CFCC strands in double-T (DT) girders. Eight DT prestressed girders fabricated with high strength concrete were tested. Four DT girders were prestressed with CFRP Leadline tendons while the other four DT girders were prestressed with carbon fiber composite cable (CFCC) strands.

Construction of Test Girders

Two groups of four DT girders were fabricated. The first group of girders is designated as CDT1-1, CDT1-2, CDT1-3 and CDT1-4 and prestressed with Leadline tendons, while the second group of girders is designated as CDT2-1, CDT2-2, CDT2-3 and

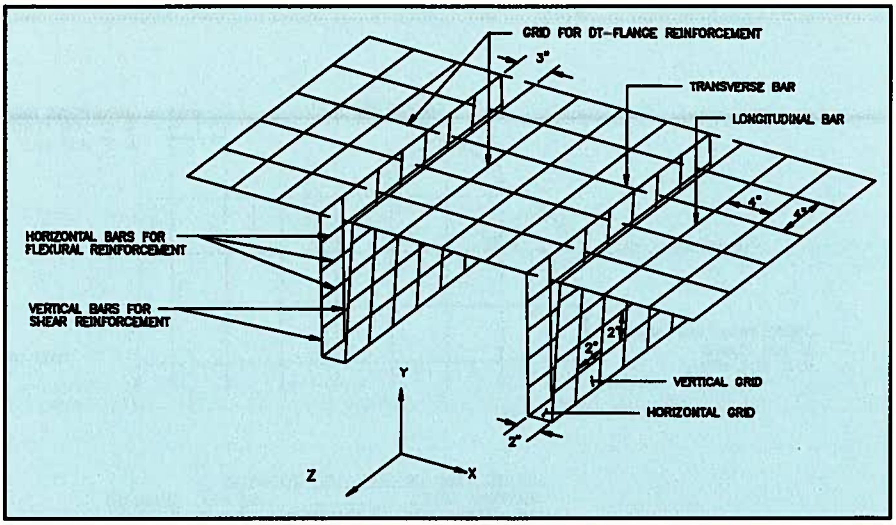

Fig. 3. Three-dimentional CFRP cage arrangement for flexural and shear reinforcement for DT Girders CDT1-1, 2, 3 and 4.

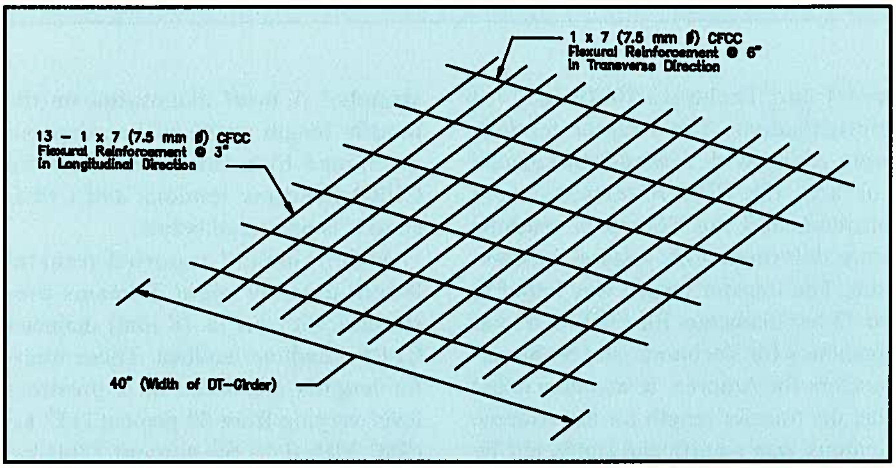

Fig. 4. DT-flange reinforcement.

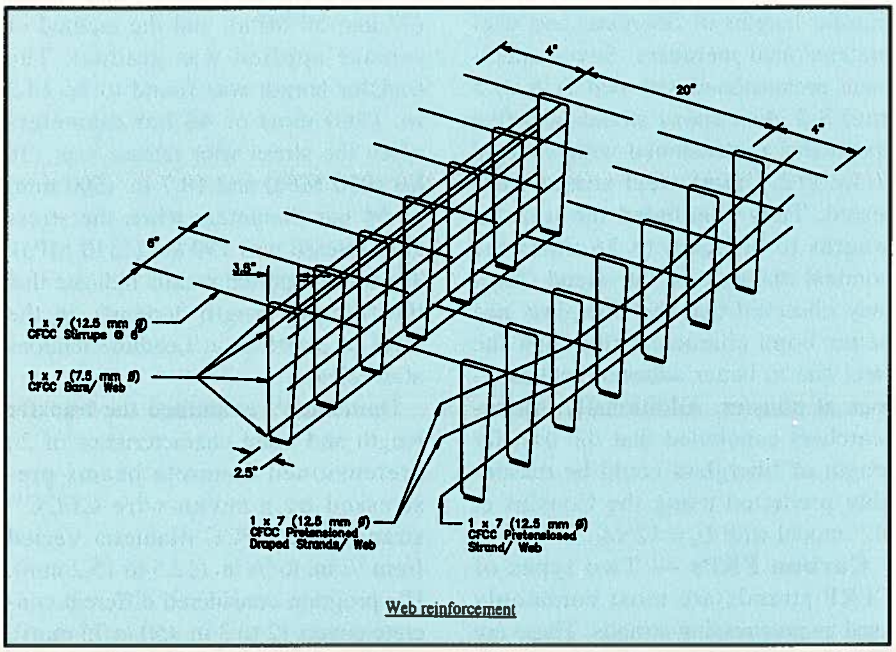

Fig. 5. Details of CFCC flexural and shear reinforcement for DT Girders CDT2-1, 2, 3 and 4.

CDT2-4 and prestressed with CFCC strands.

These girders are designed as simply supported girders. However, they are currently being used for the construction of continuous[21] prestressed concrete bridge models; hence, the notation CDT, which stands for continuous double-T bridge model. The first digit refers to the type of strand used (1 for Leadline tendon and 2 for CFCC strand); the last digit refers to the DT girder number. In this paper, DT girders are simply supported.

Basic characteristics of the material for Leadline[23] tendons and CFCC[18] strands are presented in Tables 1 and 2, respectively. Fig. 1 shows the details of Girders CDT1-1, 2, 3, 4 and CDT2-1, 2, 3, 4 with their elevation, cross sections, and positions and sizes of tendons/strands. The span of each girder is 19.33 ft (5890 mm). Each DT girder is 13.5 in. (345 mm) deep and its flange is 40 in. (1015 mm) wide.

The center-to-center distance between the two webs of each DT girder is 20 in. (510 mm) and the thickness of flange is 1.5 in. (38 mm). The widths of each web at the bottom of the DT girder and at the flange are 3.5 and 4.5 in. (90 and 115 mm), respectively. Six tendons/strands per DT girder were pretensioned prior to placing the concrete. Two top (draped) Leadline tendons are of 0.3 in. (8 mm) diameter while the bottom tendon in each web (straight) is of 0.4 in. (10 mm) diameter. The diameter of each CFCC strand is 0.5 in. (12.5 mm).

Reinforcement Details

Arrangements of reinforcements for girders CDT1 and CDT2 are described below:

Girders CDT1 — For this group of girders, four CFRP reinforcing cages using NEFMAC™* CFRP grids of 2 x 2 in. (50 x 50 mm) spacing were fabricated for flexural and shear reinforcements. A typical "NEFMAC" two-dimensional grid with its specification is shown in Fig. 2.

Note that the size of each grid in the flange is 4 x 4 in. (100 x 100 mm) while the size of each grid in the web

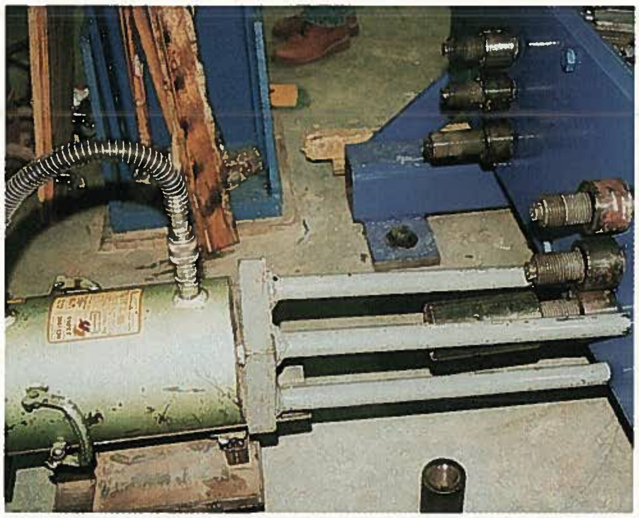

Fig. 6.
Arrangement at live end for prestressing DT Girders CDT1-1, 2, 3 and 4.

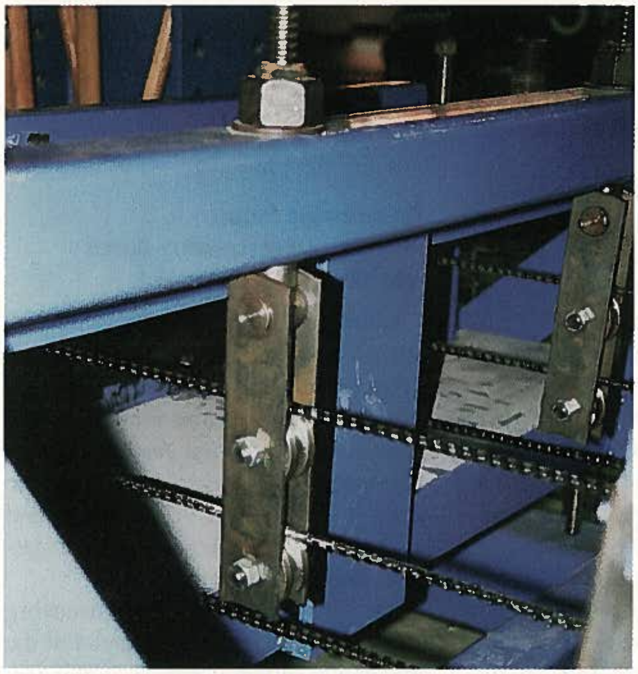

Fig. 7.
Hold-up arrangement for CFRP Leadline prestressing tendons.

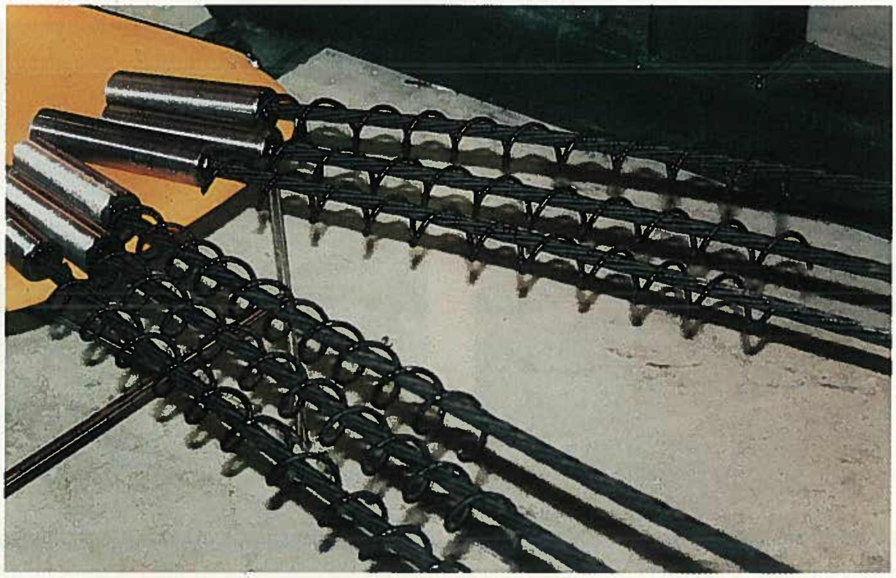

Fig. 8. CFCC strands with anchor head and CFRP spirals.

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*NEFMAC™ denotes trade mark name; provided by Autocon Equipment Incorporated, Canada.[24]

Fig. 9. Girders CDT2-1, 2 prior to casting concrete.

is 2 x 2 in. (50 x 50 mm). The three-dimensional CFRP cage arrangement is shown in Fig. 3.

Girders CDT2 — For this group of girders, CFCC strands of 0.3 in. (7.5 mm) diameter are used to provide flexural reinforcement in the flanges. The strands are laid in transverse and longitudinal directions with a spacing of 6 and 3 in. (152 and 76 mm), respectively, as shown in Fig. 4. Two-legged 0.5 in. (12.5 mm) diameter CFCC stirrups with a spacing of 6 in. (152 mm) are provided for shear reinforcement in each web. In addition, four longitudinal CFCC strands of 0.3 in. (7.5 mm) diameter are provided on each side of each web. The details of the shear reinforcement are shown in Fig. 5.

Prestressing Setup, Release of Prestressing Force and Strain Measurements

Details of the arrangement of prestressing strands in the DT girders are given elsewhere.[21] For prestressing a girder, each Leadline tendon/CFCC strand was tensioned (before casting of concrete in the form) by a hydraulic jack at the live end of the girder and anchored to the bulkhead using a special anchorage system.[22]

The arrangement for prestressing DT Girders CDT1-1, 2, 3, and 4 at the live end is shown in Fig. 6. In this figure, it is shown that the straight Leadline tendon (bottom of Web B) is connected to the hydraulic jack for tensioning. The connection between the hydraulic jack and the tendon is made by means of a connecting steel rod, which passes through a coupler that is screwed on to the Leadline anchor head.

To provide the desired draped profile of the tendons, internal hold-down and hold-up arrangements, following recommendations of earlier investigations,[22] were installed. A typical hold-up arrangement for CFRP Leadline prestressing tendons is shown in Fig. 7.

A set of CFCC strands with pre-attached anchor heads is shown in Fig. 8. These anchor heads are placed on the dead end side of the girders and are connected to the load cells (positioned between the lock nut and bulkhead). It is also shown in Fig. 8 that these CFCC strands are provided with CFRP spirals around them within the transfer length.

These spirals around the strands aid in preventing the development of cracks at the transfer of prestress to the concrete. A typical view of Girders CDT2-1 and 2, prior to casting the concrete, is shown in Fig. 9. This figure also shows the details of CFCC reinforcements for flexure and shear in Girders CDT2-1 and 2.

The concrete mix was cast into the girder forms and after it had gained a strength of 7000 psi (48 MPa) (at 7

Fig. 10. Sudden release of Leadline™ prestressing tendons using hand-held saw.

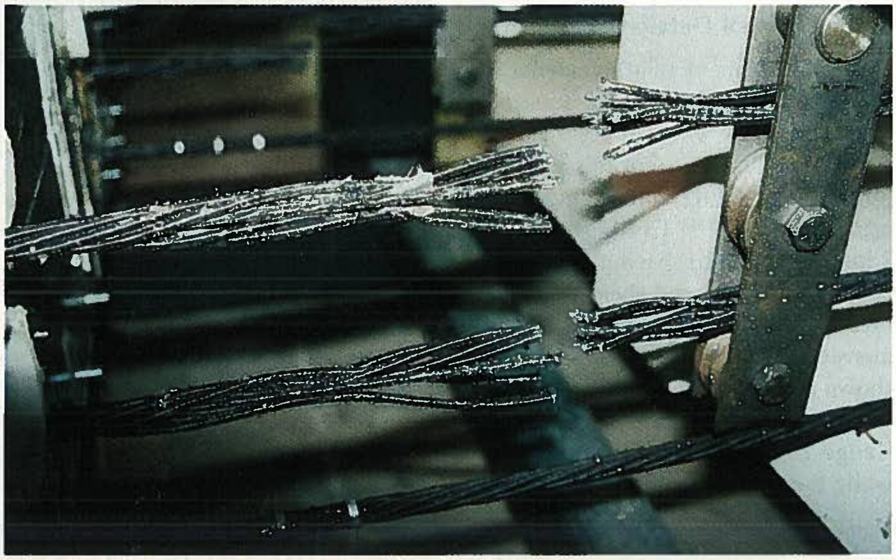

Fig. 11. Typical CFCC strands after sudden release of prestressing forces.

days), the tendons/strands were released by means of a hand-held saw as shown in Figs. 10 and 11. Fig. 10 shows a typical case for the sudden release of prestressing forces in Leadline rods using a hand-held saw, while Fig.11 shows the sudden release of prestressing forces in CFCC strands.

Measurements of concrete strain at the centroid of the prestressing strands were made by two persons using detachable mechanical gauges with equally spaced DEMEC target points (see Fig. 12). The average spacing between each pair of target points at midspan was 7.9 in. (200 mm). Closer spacing between target points was used at the two ends of each girder. The concrete strain recorded was determined by averaging the readings taken by both persons.

The prestressing force in each tendon was monitored using load cells at the dead ends of the girders. The average prestressing force in the draped Leadline tendons was approximately 17 kips (76 kN). In the straight Leadline tendons, the average prestressing force was approximately 19 kips (85 kN). Therefore, the average stresses in the 0.3 and 0.4 in. (8 and 10 mm) Leadline tendons were 239 and 170 ksi (1650 and 1170 MPa), respectively, as shown in Table 3.

The data in Table 4 indicate that the average prestressing force in the CFCC strands was approximately 16.6 kips (74 kN), producing an average stress of 140 ksi (971 MPa). It is also shown in Table 3 that the average elongations of the 0.3 and 0.4 in. (8 and 10 mm) Leadline tendons were approximately 3.24 and 2.24 in. (80 and 60 mm), respectively. In Table 4, the data show that the average elongation of the CFCC strands was 2.7 in. (69 mm).

RESULTS AND DISCUSSION

The measured transfer lengths at the live and dead ends of the girders and the effects of parameters such as level of release of prestress, time elapsed after transfer of prestress and long-term effect on transfer lengths of CFRP Leadline tendons/CFCC strands (represented by the CDT1/CDT2 groups of girders) are presented in this section. Finally, a model for predicting the transfer length of CFRP Leadline tendons/CFCC strands based on a regression analysis is proposed and a comparison of the measured results with the theoretically predicted values is made.

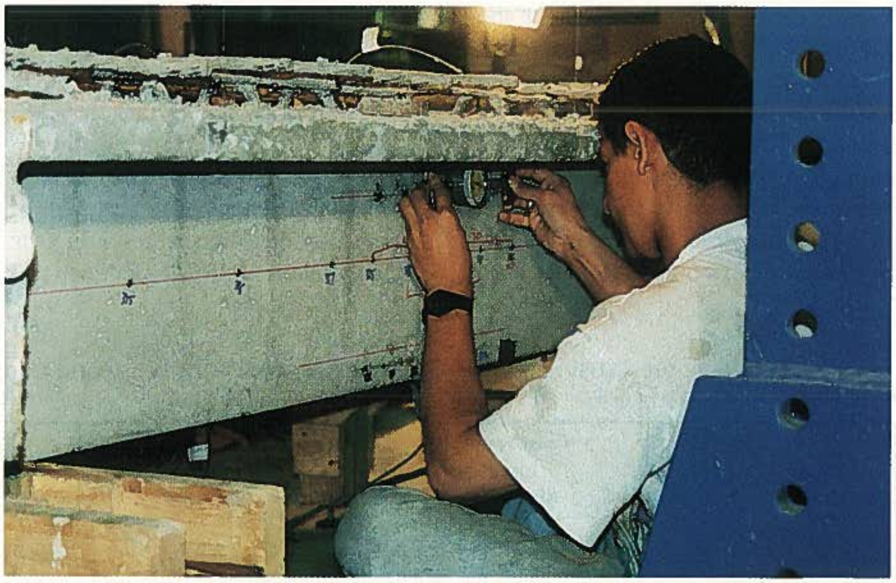

Fig. 12. Concrete strain measurements using DEMEC gauge and DEMEC target points.

METHOD OF RELEASE

The last two columns of Table 3 show the average transfer length for Leadline tendons at the live and dead ends, respectively, for Girders CDT1-1, 2, 3, and 4. Note that these results correspond to the sudden release of the prestressing force, except in the case of Girder CDT1-1. In this girder (CDT1-1), the prestress was released slowly at the live end and released suddenly at the dead end.

It is observed that the transfer lengths of the CFRP Leadline tendons at the live end of the girders are slightly larger than the transfer lengths at the dead end. Furthermore, slow release results in a larger transfer length than sudden release (70 times the average diameter of Leadline tendons versus 55 times the average diameter). Table 4 shows a similar difference in transfer lengths of CFCC strands in Girder CDT2.

Examination of this table also suggests that slow detensioning of CFCC strands results in a larger transfer length in comparison to sudden release (39 times the diameter of CFCC strands versus 34 times the diameter). Furthermore, it is worth mentioning that the difference in transfer lengths for slow and sudden release of CFRP Leadline tendons is about 28 percent; the corresponding difference for CFCC strands is about 15 percent.

Thus, the difference in transfer lengths obtained for slow release and sudden release of CFRP strands is in contrast to what is well known for steel strands (Mitchell et al.[4]). In their results, flame-cutting of the steel strands resulted in transfer lengths of about 6 to 30 percent greater than those determined for slowly released steel strands.

Effects of Level of Release of Prestress Force

In order to examine the effect of level of release of prestress force on the transfer lengths of Leadline tendons and CFCC strands, the variations of concrete strain along the span of Girders CDT1-4 and CDT2-1 for three levels of release of prestress (i.e., 33, 67, and 100 percent) are shown in Figs. 13 and 14, respectively. Here, 33 percent release refers to the top two (draped) tendons being released at the same time; 66 percent release refers to the top four draped tendons being released and 100 percent release refers to all tendons being released.

Note that the Leadline tendons are released suddenly at both ends while the CFCC strands are released slowly at the live end and suddenly at the dead end. Figs. 13 and 14 show that the concrete strain profile along the girders is not following a straight-line pattern. This is attributed to the draped profile of the tendons/strands due to the two internal hold-down and hold-up arrangements at the bulkhead. Note that the two hold-downs were cut before the release of the tendons/strands.

From Figs. 13 and 14, transfer length is determined by the 95 percent AMS (Average Maximum Strain) method;[25] that is, by measuring the distance from the end of the member to the point of intersection of a line representing the strain variation in the transfer zone and a horizontal line representing 95 percent of the average of the strains contained within the strain plateau of the effective prestressing force. It is shown that there is no appreciable change in transfer length with the increase in level of release of prestressing force for both the CFRP Leadline tendons and the CFCC strands.

Table 3. Details of prestressing forces, elongation, end slip at release and transfer lengths of Girders CDT1-1, -2, -3, -4.

Girder designation	Web	Tendons	Prestressing force kips (kN)	Stress ksi (GPa)	Elongation in. (mm)	End slip		Measured transfer lengths	
						Live end in. (mm)	Dead end in. (mm)	Live end in. (mm)	Dead end in. (mm)
CDT1-1	A	A1	18 (80.1)	252 (1.74)	3.6 (90)	0.21 (5.2)	N/A	25.0 (635)*	18.9 (480)†
		A2	19 (84.5)	266 (1.83)	3.8 (97)	N/A	N/A		
		A3	21 (93.4)	189 (1.30)	2.4 (60)	0.07 (2.2)	N/A		
	B	B1	16 (71.2)	224 (1.54)	3.2 (81)	0.11 (2.8)	N/A	22.4 (570)*	17.5 (445)†
		B2	16 (71.2)	224 (1.54)	3.1 (78)	N/A	N/A		
		B3	22 (97.9)	198 (1.36)	2.5 (64)	N/A	N/A		
CDT1-2	A	A1	17 (75.6)	238 (1.64)	3.2 (82)	N/A	N/A	18.9 (480)†	18.0 (460)†
		A2	18 (80.1)	252 (1.74)	3.5 (89)	N/A	N/A		
		A3	18 (80.1)	162 (1.12)	2.3 (57)	N/A	N/A		
	B	B1	16 (71.2)	224 (1.54)	3.0 (76)	N/A	N/A	—	—
		B2	17 (75.6)	238 (1.64)	3.4 (86)	N/A	N/A		
		B3	18 (80.1)	162 (1.12)	2.3 (57)	N/A	N/A		
CDT1-3	A	A1	17 (75.6)	238 (1.64)	3.1 (79)	0.31 (7.9)	0.21 (5.3)	20.0 (510)†	19.5 (495)†
		A2	17 (75.6)	238 (1.64)	3.0 (76)	0.13 (3.3)	0.12 (3.0)		
		A3	17 (75.6)	153 (1.05)	2.3 (57)	0.03 (0.8)	0.09 (2.3)		
	B	B1	20 (89.0)	280 (1.93)	3.0 (76)	0.08 (2.0)	0.17 (4.3)	16.5 (420)†	16.0 (410)†
		B2	16 (71.2)	224 (1.54)	3.3 (83)	0.04 (1.0)	0.04 (1.0)		
		B3	15 (66.7)	135 (0.93)	2.1 (54)	0.05 (1.3)	0.06 (1.5)		
CDT1-4	A	A1	17 (75.6)	238 (1.64)	3.1 (79)	0.08 (2.0)	0.15 (3.8)	19.5 (495)†	18.9 (480)†
		A2	17 (75.6)	238 (1.64)	3.4 (86)	0.20 (5.1)	0.16 (4.1)		
		A3	20 (89.0)	180 (1.24)	2.0 (51)	0.10 (2.5)	0.15 (3.8)		
	B	B1	18 (80.1)	252 (1.74)	3.0 (76)	0.09 (2.3)	0.13 (3.3)	20.0 (510)†	19.5 (495)†
		B2	14 (62.3)	196 (1.35)	3.1 (79)	0.13 (3.3)	0.05 (1.3)		
		B3	20 (89.0)	180 (1.24)	2.0 (51)	0.07 (1.8)	0.09 (2.3)		

Note 1: A1, A2, B1 and B2 are 8 mm draped tendons.
Note 2: A3 and B3 are 10 mm bottom straight tendons.
*Slow release.
†Sudden release.

Variation of Prestressing Force

The variation of prestressing force with time, measured at the dead end, during the slow release of the prestressing force in Strand B1 at the live end of Girder CDT2-1 is shown for all six CFCC strands in Fig. 15. Also, the variation in prestressing forces, measured at the dead end, during sudden release of Strand B1 at its dead end is shown in Fig. 16. Hence, in these figures the prestressing forces are not the actual prestressing force in the strands within the concrete but are, in fact, a measure of forces in the portion of the strands lying between the end of the girder and the bulkhead at the dead end.

Thus, these figures represent the variation of apparent prestressing forces in the strands with time. Examination of Fig. 15 suggests that when Strand B1 is released slowly at the live end, the apparent prestressing force in Strand B1 (the released strand), as well as the other unreleased strands, decreases during the slow release

Table 4. Details of prestressing forces, elongation, end slip at release and transfer lengths of Girders CDT2-1, -2, -3, -4.

Girder designation	Web	Tendons	Prestressing force kips (kN)	Stress ksi (GPa)	Elongation in. (mm)	End slip Live end in. (mm)	End slip Dead end in. (mm)	Measured transfer lengths Live end in. (mm)	Measured transfer lengths Dead end in. (mm)
CDT2-1	A	A1	15.8 (70.3)	134.1 (925)	2.5 (64)	0.04 (1.0)	N/A	21.0 (533)*	18.5 (470)†
		A2	15.4 (68.5)	130.7 (901)	3.1 (79)	0.08 (2.0)	N/A		
		A3	15.0 (66.7)	127.3 (878)	2.4 (61)	0.09 (2.3)	0.04 (1.0)		
	B	B1	16.3 (72.5)	138.4 (954)	2.5 (64)	0.04 (1.0)	0.03 (0.8)	20.0 (508)*	13.0 (330)†
		B2	16.3 (72.5)	138.4 (954)	2.9 (74)	0.01 (0.3)	N/A		
		B3	15.6 (69.4)	132.4 (913)	2.4 (61)	0.03 (0.8)	0.04 (1.0)		
CDT2-2	A	A1	16.3 (72.5)	138.4 (954)	2.8 (71)	0.05 (1.3)	0.10 (2.5)	19.5 (495)*	18.5 (470)†
		A2	16.4 (72.9)	139.2 (959)	2.9 (74)	0.04 (1.0)	0.04 (1.0)		
		A3	16.1 (71.6)	136.7 (942)	2.4 (61)	0.07 (1.8)	0.02 (0.5)		
	B	B1	15.6 (69.4)	132.4 (913)	2.4 (61)	0.04 (1.0)	0.02 (0.5)	18.9 (480)*	18.0 (457)†
		B2	15.8 (70.3)	134.1 (924)	2.8 (71)	0.05 (1.3)	N/A		
		B3	16.7 (74.3)	141.8 (977)	2.9 (74)	0.02 (0.5)	0.09 (2.3)		
CDT2-3	A	A1	17.4 (77.4)	147.7 (1018)	2.9 (74)	0.06 (1.5)	0.09 (2.3)	23.0 (584)†	18.0 (457)†
		A2	16.5 (73.4)	140.1 (966)	2.5 (64)	0.04 (1.0)	0.05 (1.3)		
		A3	16.8 (74.7)	142.6 (983)	2.5 (64)	0.02 (0.5)	N/A		
	B	B1	16.6 (73.8)	140.9 (972)	2.9 (74)	0.06 (1.5)	N/A	16.5 (419)*	16.0 (406)†
		B2	17.1 (76.1)	145.2 (1001)	2.6 (66)	0.05 (1.3)	N/A		
		B3	17.7 (78.7)	150.3 (1036)	2.9 (74)	0.03 (0.8)	N/A		
CDT2-4	A	A1	16.8 (74.7)	142.6 (983)	2.8 (71)	0.05 (1.3)	N/A	18.9 (480)†	16.0 (406)†
		A2	18.7 (83.2)	158.7 (1095)	2.8 (71)	0.04 (1.0)	N/A		
		A3	17.0 (75.6)	144.3 (995)	2.5 (64)	0.03 (0.8)	N/A		
	B	B1	18.1 (80.5)	153.6 (1059)	2.9 (74)	0.05 (1.3)	N/A	16.0 (406)†	15.5 (394)†
		B2	17.5 (77.8)	148.6 (1024)	2.9 (74)	0.05 (1.3)	N/A		
		B3	17.4 (77.4)	180 (1.24)	2.5 (64)	0.05 (1.3)	N/A		

Note 1: A1, A2, A3, B1, B2 and B3 are 12.5 mm CFCC strands.
Note 2: N/A: Results are not available.
*Slow release.
†Sudden release.

time. This is attributed to the loss of force in the strands due to the movement of the girder towards the dead end of the strands (after the release of Strand B1 at its live end).

Nonetheless, it is seen from Fig. 16 that when Strand B1 is suddenly released at its dead end, the apparent prestressing force in the unreleased strands starts increasing as the force in Strand B1 (the released strand) goes to zero. This is also attributed to the tendency of the girder to move towards the live end (in this case) after the release of Strand B1 at its dead end. Due to this girder movement, a portion of the unreleased strands between the end of the girder and the bulkhead are stretched further; hence, the load cells mounted at the dead end record an increased force in the strands.

To examine the time taken to release the prestress force in a tendon/strand during slow and sudden release conditions, the variation of the prestressing forces in all six CFCC strands with time is shown in Figs. 17 and 18, during slow and sudden release, respectively. The total time over which the force in the strand shows variation is taken as the time of release of the prestressing force.

The average release time is computed by dividing the sum of the total time of release of prestressing forces in each strand by the number of strands. It is observed that the average time of release of prestressing force when the strand is released slowly is 34 seconds, while the average time of release of prestressing force when it is released suddenly is only one second.

Long Term Transfer Length

To study the effect of time on the transfer length of Leadline tendons after the release of the prestressing force, the distribution of concrete strain along the span of Girder CDT1-4 is shown in Fig. 19 for different periods (i.e., at transfer, 14, 28 and 300 days after transfer of prestress to the concrete). As expected, it can be seen that the concrete strain increases with time elapsed after the transfer of prestress, due to the combined effect of shrinkage, creep and relaxation of stress in the tendons.

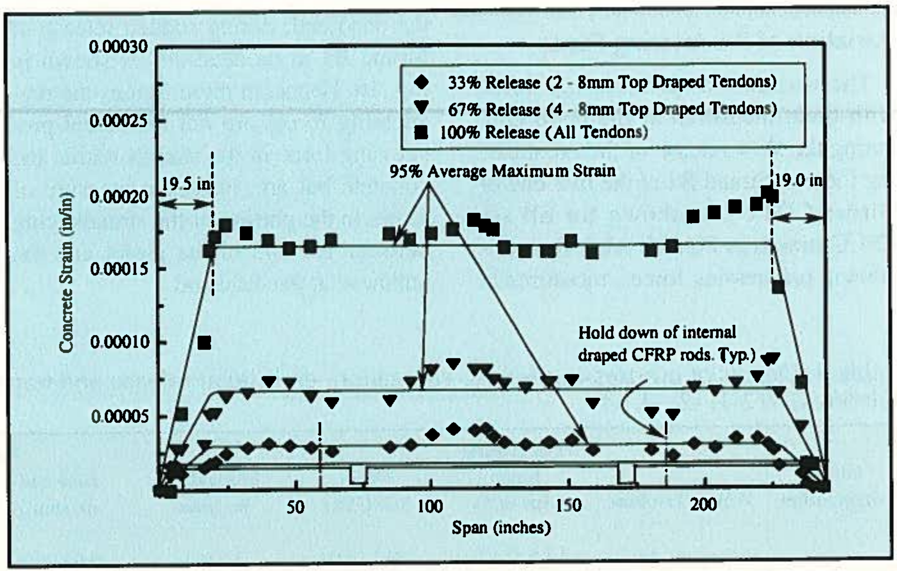

Fig. 13. Transfer length at release of prestressing forces of Girder CDT1-4, Web A.

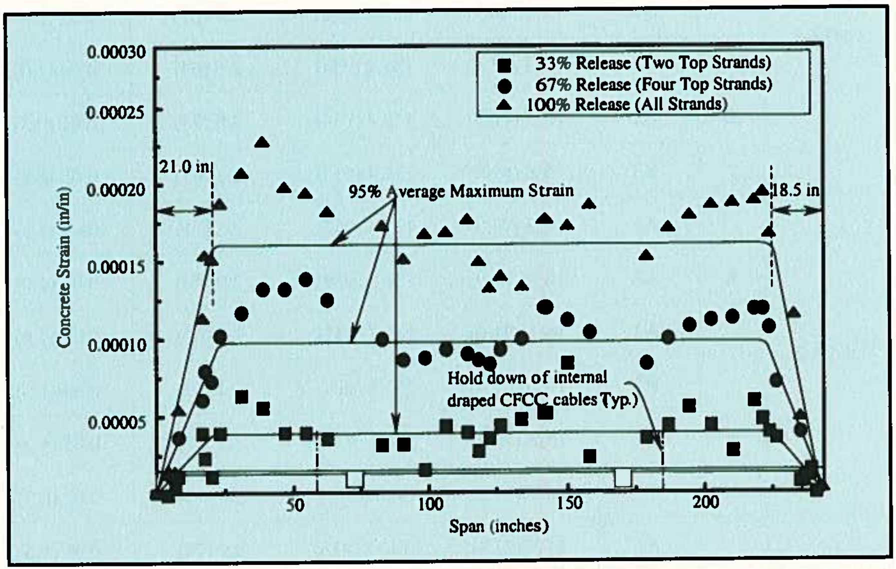

Fig. 14. Transfer lengths at release of prestressing forces of Girder CDT2-1, Web A.

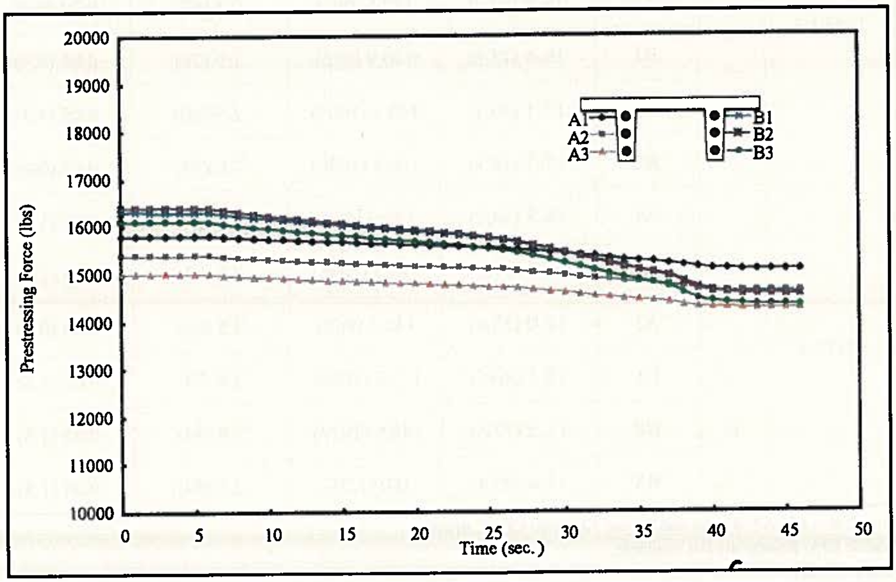

Fig. 15. Slow release of prestressing strand B1 at live end of Girder CDT2-1.

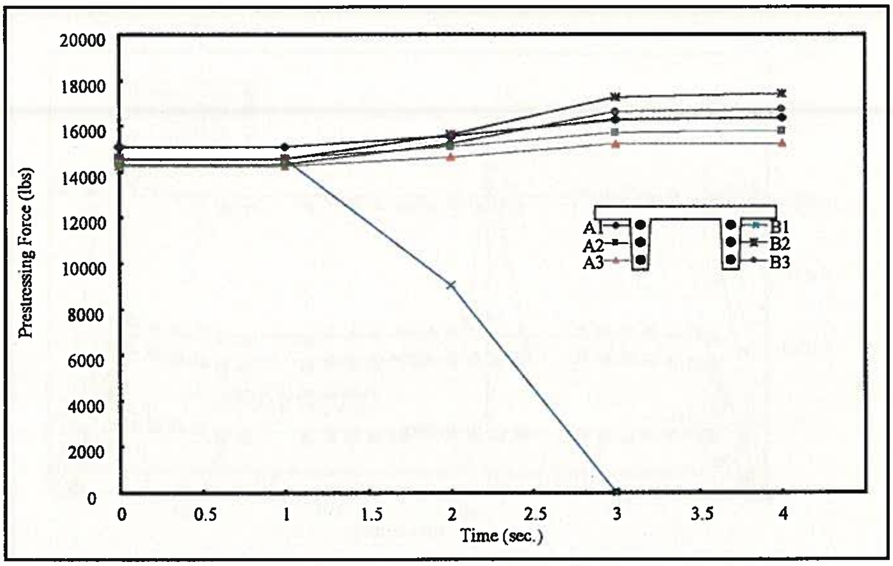

Fig. 16. Sudden release of prestressing strand B1 at dead end of Girder CDT2-1.

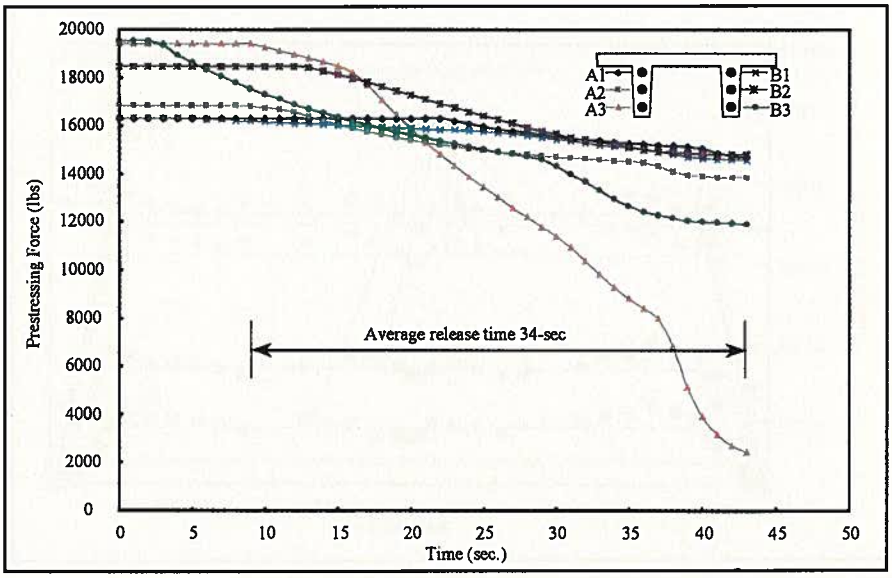

Fig. 17. Slow release of prestressing strands at live end of Girder CDT2-1.

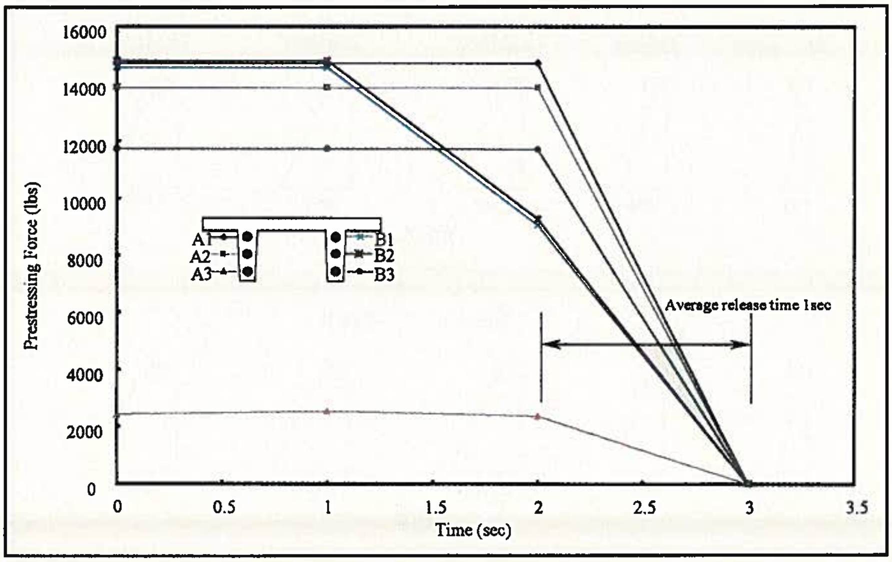

Fig. 18. Sudden release of prestressing strands at dead end of Girder CDT2-1.

Nevertheless, it is shown that there is no significant effect of time on the transfer length of the tendons; that is, the increase in transfer length 300 days after transfer is only about 7.8 percent. Similarly, to examine the effect of time on transfer length of CFCC strands, the variation in concrete strain for different periods of measurement (i.e., at transfer, 7, 122, 214 and 391 days after transfer of prestress to the concrete) along Girder CDT2-1 is shown in Fig. 20. It is observed that the concrete strain for Girder CDT2-1 also increases with time.

It is also observed that there is, on average, a 7 percent increase in the transfer length 391 days after prestress transfer. Thus, it may be noted that the long-term effect (i.e., the effect of elapsed time after transfer of prestress to concrete) on the transfer lengths of CFCC strands and CFRP Leadline tendons is almost the same as that reported for steel strands (Mitchell et al.[4]).

Effect of Creep on Concrete Strain

To examine the long-term creep effect, the strain distribution at the midspans of Girders CDT1-1, 2, 3, and 4 was monitored for 393 days, while for Girders CDT2-1, 2, 3, and 4 it was monitored for 431 days. The strain distributions for Girders CDT1-1 and CDT2-1 are shown in Figs. 21 and 22, respectively. In the case of Girder CDT1-1, 393 days after the transfer of prestress, the average strain in the concrete at midspan of the girder increased to about 3.5 times that of the strain at the time of transfer.

In the case of Girder CDT2-1, there is an increase in strain of about 4.8 times after a monitoring period of 431 days. This difference in concrete strains in Girders CDT1 and CDT2, prestressed with CFRP Leadline tendons and CFCC strands, respectively, may be attributed to the axial rigidity (*EA*, i.e., modulus times area of the tendons/strands) and to the different bond characteristics of Leadline tendons and CFCC strands with the concrete. Thus, it is noted that the creep effect is more significant in the case of Girder CDT2-1, which was prestressed with

CFCC strands, than that in the case of Girder CDT1-1, which was prestressed with Leadline tendons.

Figs. 23 and 24 show the nonlinear variation of concrete strain with time at the top and bottom of midspan for Girders CDT1-1 and CDT2-1, respectively. It is observed that for a fixed time, the strain at the bottom of the web is higher than at the top, irrespective of the girder types. This is attributed to the presence of tendons at the bottom, which increase the net compressive strain in the concrete. It is also shown that the concrete strain is increasing with time at the top as well as at the bottom for both groups of girders (CDT1 and CDT2 types).

In the above, it is worth noting that the rate of increase in strain is more significant (for both groups of girders) immediately after the release of prestressing force. As time passes, the strain levels out to a constant value. By examining the slope of the nonlinear variation of concrete strain with time for both girders, it is observed that the time rate of increase in concrete strain is larger in the case of Girder CDT2 than in the case of Girder CDT1.

Transfer Length Correlation

To examine the applicability of the currently available empirical model[19] for determining the transfer length for Leadline tendons and CFCC strands in DT girders made of high strength concrete, the relationships between the measured transfer length and other primary variables such as prestress at transfer, diameter of the strands and concrete strength at transfer are shown in Figs. 25 and 26. Fig. 25 corresponds to Leadline tendons while Fig. 26 corresponds to CFCC strands.

Based on a regression analysis, the following modifications in the transfer length coefficient (α_t) of the model developed by Mahmoud et al.[19] for the transfer length of Leadline tendons and CFCC strands are proposed:

$$L_t = \left(f_{pi}\, d_b\right) / \left(\alpha_t\, f'^{\,0.67}_{ci}\right) \text{ mm} \qquad (4)$$

where

α_t = 1.95 for Leadline tendons

α_t = 2.12 for CFCC strands

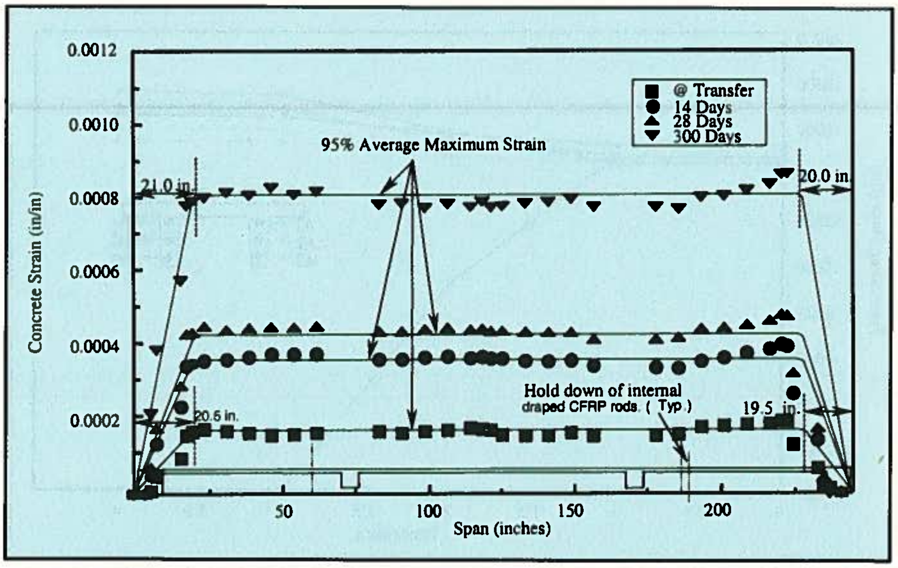

Fig. 19. Time effect on transfer length of Girder CDT1-4, Web A.

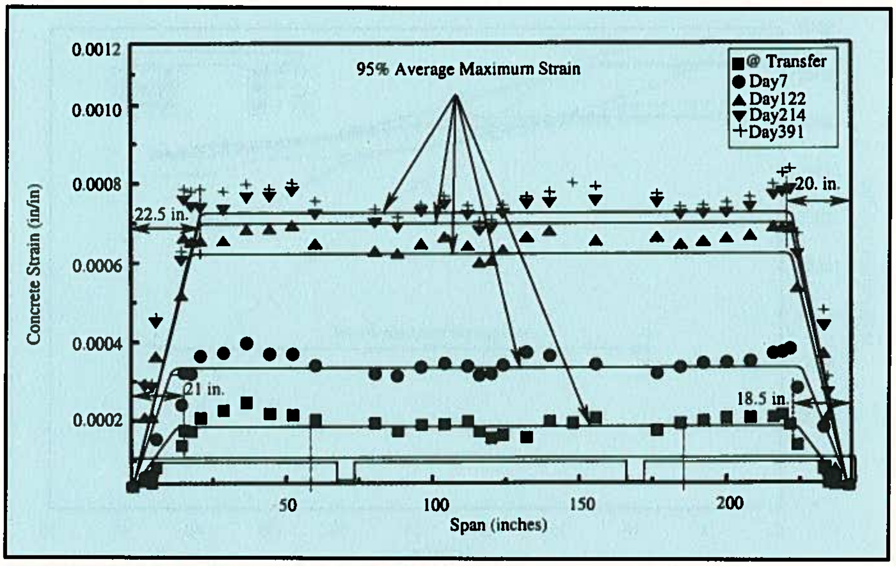

Fig. 20. Time effect on transfer length of Girder CDT2-1, Web A.

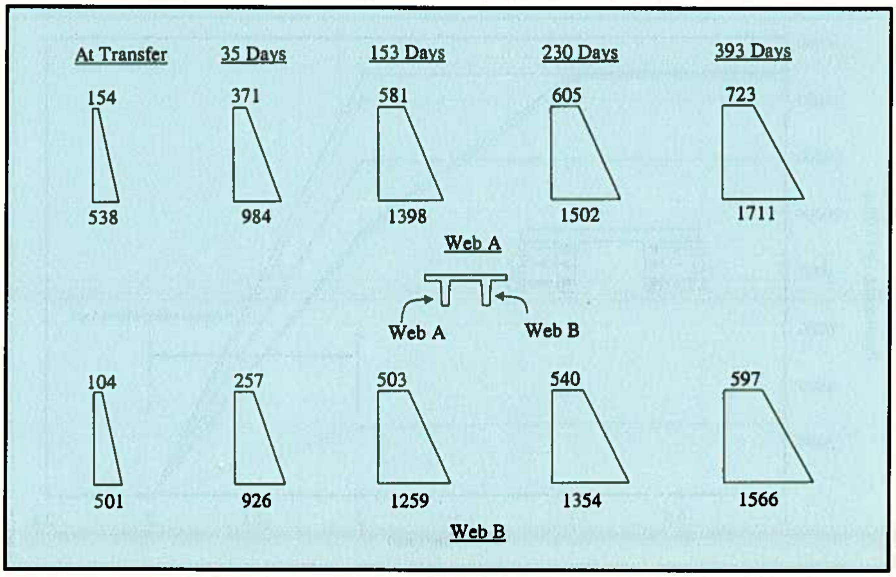

Fig. 21. Strain distribution at midspan of Girder CDT1-1 (μ in. per in.).

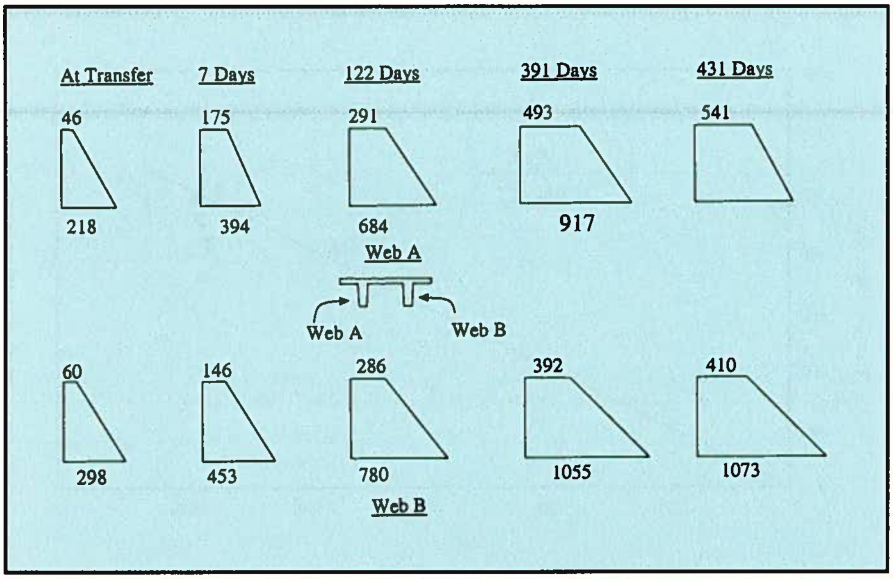

Fig. 22. Strain distribution at midspan of Girder CDT2-1 (μ in. per in.).

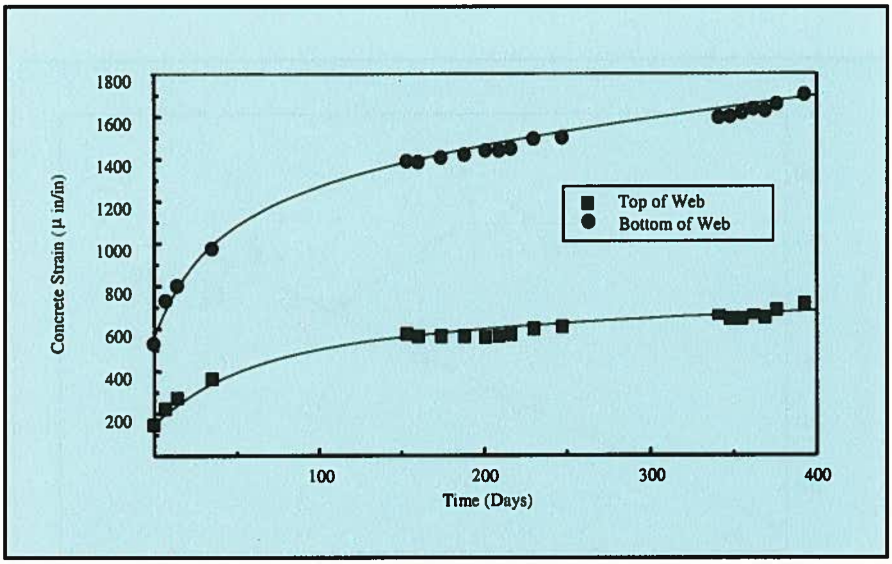

Fig. 23. Rate of increase in strains at top and bottom of Girder CDT1-1, Web A.

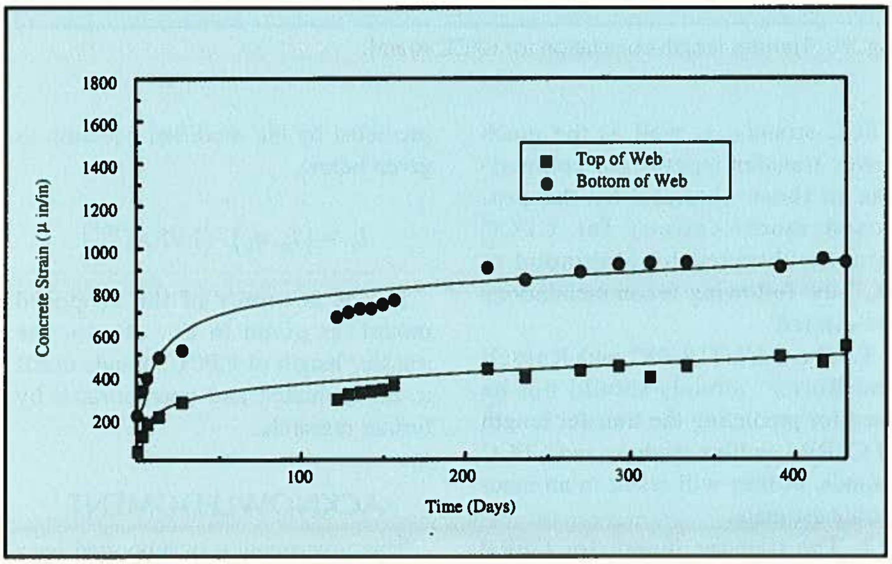

Fig. 24. Rate of increase in strains at top and bottom of Girder CDT2-1, Web A.

It should be noted that the proposed value of the constant (α_t) for Leadline tendons is close to the value developed by Mahmoud et al.[19] but differs significantly for CFCC strands. In this modified model, the transfer length coefficient (α_t) for CFCC strands is 2.12, while the transfer length coefficient is 4.8 in the model of Mahmoud et al.[19]

COMPARISON OF TRANSFER LENGTHS

Figs. 27 and 28 represent a bar chart comparison of the transfer length data predicted by the proposed modifications and those of other researchers[6,19,25] for Leadline tendons and CFCC strands, respectively. In these two figures, Letters A and B with the girder numbers represent Webs A and B of a particular girder. Each column in this chart represents the value of the transfer length of the strand used in a corresponding web using the appropriate model.

By comparing the obtained values, it is evident that ACI 318-98[6] and the Russell and Burns[25] models (developed for steel strands) highly overestimate the transfer lengths of CFRP Leadline tendons and CFCC strands. Furthermore, the results obtained by the model with a modified coefficient are closer to those of Mahmoud et al.[19] only for Leadline tendons. However, in the case of CFCC strands, the results are on an average 1.5 times higher than those of Mahmoud et al.[19]

CONCLUSIONS

Based on the results of this investigation, the following conclusions can be drawn:

1. Transfer lengths of CFRP Leadline tendons vary from 66 to 73 times the diameter of the tendon for slow release and from 47 to 59 times the diameter of the tendon for sudden release. The corresponding range of transfer lengths for CFCC strands is found to be 33 to 47 and 27 to 38 times the diameter of the strand for slow and sudden release, respectively.

2. Slow release results in larger transfer lengths for Leadline tendons and CFCC strands (about 28 and 15 percent larger, respectively) in comparison to those determined for similar strands when they are released suddenly. The differences in transfer lengths for slow and sudden release of CFRP Leadline tendons/strands is in contrast to that for steel strands, i.e., sudden release of steel strands results in a transfer length of about 6 to 30 percent greater than that determined for similar strands released gradually. The average time taken for slow release of the prestressing force in a strand is 34 seconds while for sudden release it is one second.

3. There is no appreciable change in the transfer lengths of CFRP tendons/CFCC strands with the variation in the level of release of prestressing force.

4. Long-term effects result in approximately a 7 percent increase in transfer lengths of CFRP tendons/strands over a period of one year. This result is almost the same (i.e., 6 percent) for steel strands.

5. The bond characteristics and axial rigidity (*EA*) of CFRP Leadline tendons and CFCC strands with the concrete have a significant effect on the concrete strain in the DT girders. The concrete strain is increased about 3.5 times the strain at transfer in the girders prestressed with CFRP Leadline tendons while the corresponding increase in strain in the girders prestressed with CFCC strands is 4.8 times of that at the transfer of prestress.

6. The time rate of increase in concrete strain is significant immediately after release of prestress and eventually becomes constant after about a year, irrespective of the type of strand.

7. The proposed modification in the currently available model for predicting the transfer length of CFRP Leadline tendons results in a good agreement with the measured values obtained in this investigation as well as limited data reported in the literature. However, in the case of CFCC strands, it differs significantly with those of other researchers.[19]

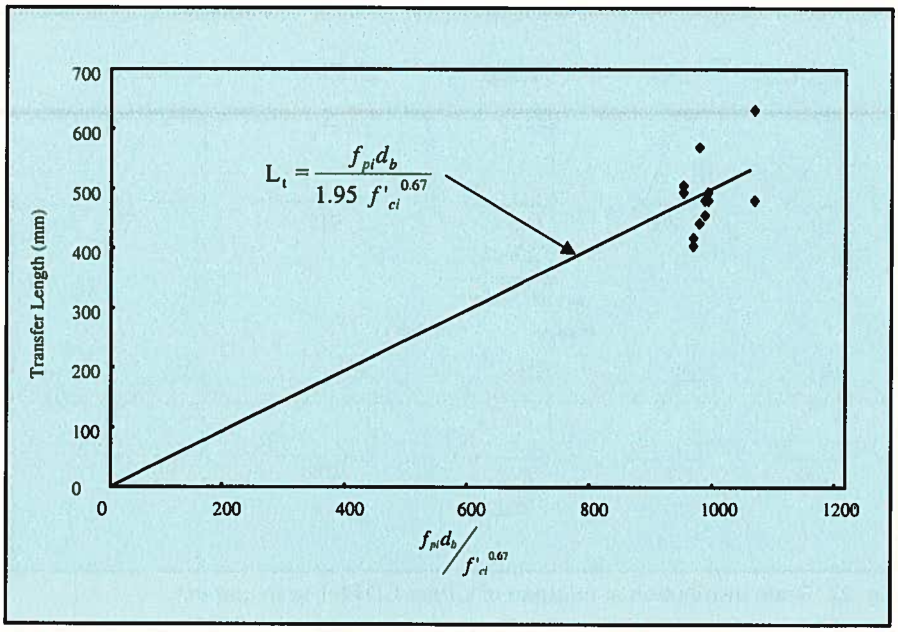

Fig. 25. Transfer length correlation for Leadline™ prestressing tendons.

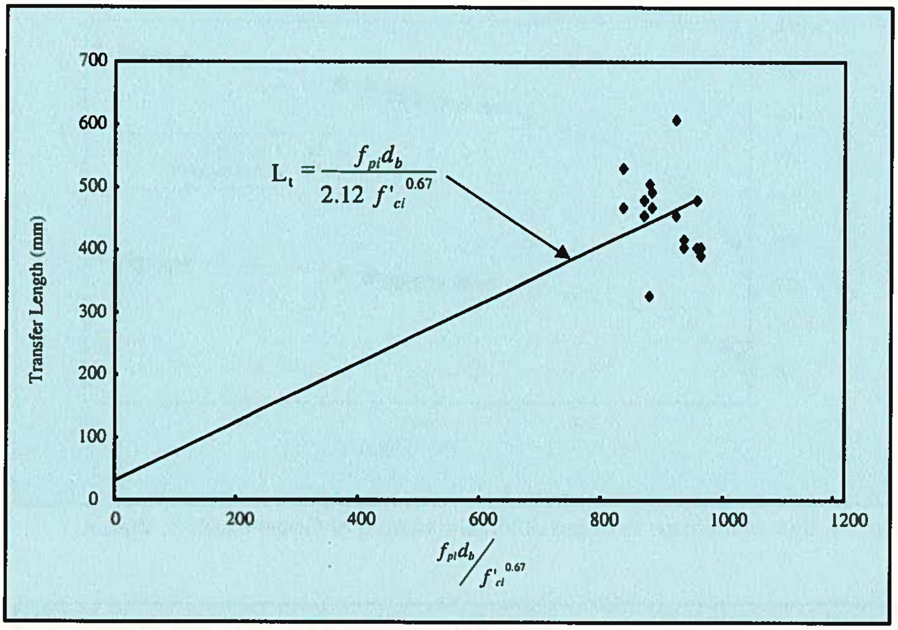

Fig. 26. Transfer length correlation for CFCC strand.

RECOMMENDATIONS

In view of the highly unconservative results[6,25] (recommended for steel strands) for the transfer length of CFRP Leadline tendons and CFCC strands, as well as the much lower transfer lengths (in comparison to those obtained by the proposed modification) for CFCC strands obtained by Mahmoud et al.,[19] the following recommendations are offered:

1. The ACI 318-98[6] and Russell and Burns[25] models should not be used for predicting the transfer length of CFRP Leadline tendons and CFCC strands, as they will result in an inaccurate estimate.

2. The transfer length for CFRP Leadline tendons can be reasonably predicted by the modified equation as given below:

$$L_t = \left(f_{pi}\, d_b\right) / \left(1.95\, f'^{\,0.67}_{ci}\right)$$

3. The accuracy of the proposed model, as given in Eq. (4), for the transfer length of CFCC strands needs to be evaluated and corroborated by further research.

ACKNOWLEDGMENT

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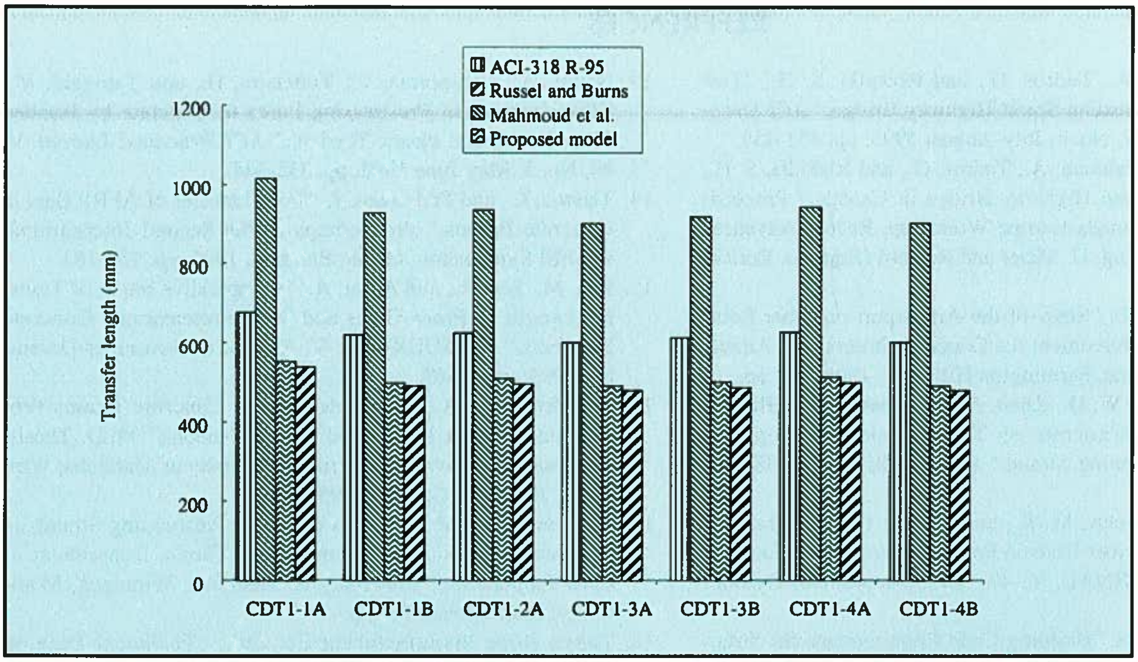

Fig. 27. Comparison of transfer length data for Leadline™ tendon.

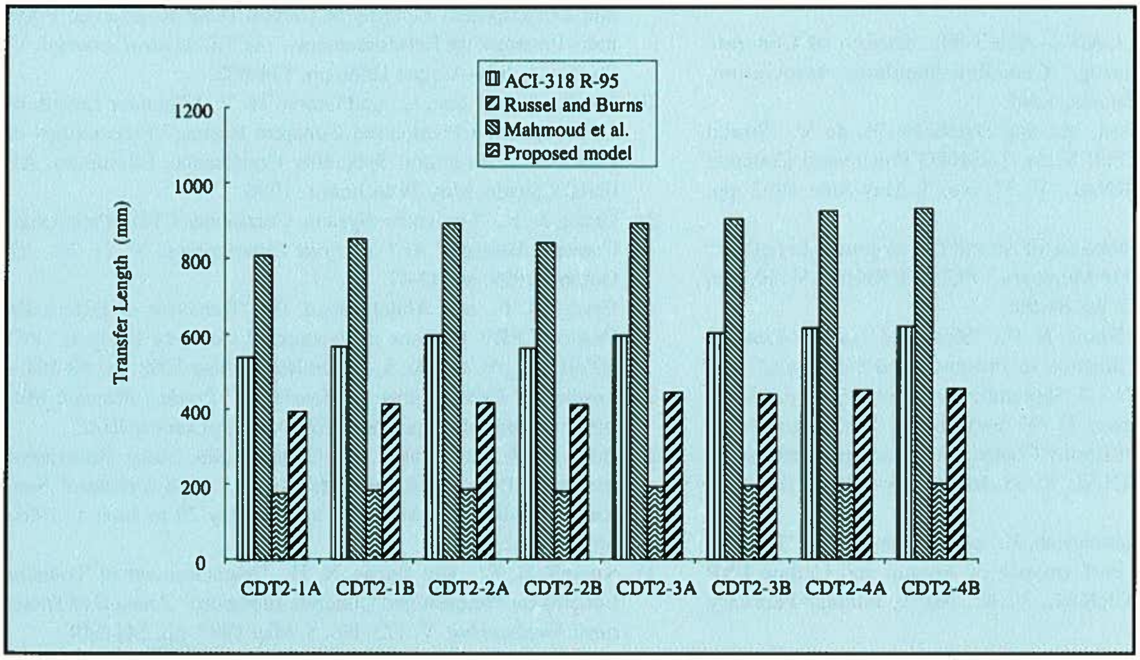

Fig. 28. Comparison of transfer length data for CFCC strand.

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APPENDIX — NOTATION

A = cross-sectional area of member
A_{ps} = cross-sectional area of prestressing strand
B = bond modulus
d_b = nominal diameter of strand
E = Young's modulus of elasticity
f'_c = specified compressive strength of conrete
f'_{ci} = compressive strength of concrete at strand release (transfer)
f_{pe} = effective prestress in strand
f_{pi} = prestress at transfer
L_t = transfer length of strand
U_t = plastic transfer bond stress
α_t = transfer length coefficient
π = 3.14159