TRANSFER LENGTHS FOR PRESTRESSED CONCRETE BEAMS CAST WITH SELF-CONSOLIDATING CONCRETE MIXTURES

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ABSTRACT

Self Consolidating Concrete (SCC) is a recent advancement in the concrete industry. SCC is a type of concrete that can be placed without consolidation and is beginning to be accepted by some state DOT's for use in highway bridge girders. SCC is not much different from conventional concrete. The constituent materials are the same, but SCC typically contains more fine aggregate and cement, and less coarse aggregate. These differences may affect the length of prestress transfer and flexural bond performance for SCC specimens when compared to conventional concrete specimens. These differences may also contribute to larger transfer lengths than those predicted by the ACI Building Code Requirements for Structural Concrete and the AASHTO Standard Specification for Highway Bridges. Currently the design recommendations offered by ACI and AASHTO have only been proven valid for conventional concrete girders. The research program compares measured transfer lengths for SCC beam specimens to those calculated using the ACI and AASHTO transfer length equations.

Keywords: Transfer Length, Self-Consolidating Concrete, High Strength, Prestressed Bridge Girders

INTRODUCTION

Self-Consolidating Concrete (SCC) is becoming widely used as a substitute to conventional concrete mixtures in many concrete structures in Japan and Europe. Applications of SCC within both Japan and Europe have been associated with bridges, buildings, and tunnel construction.[1] Japan has been incorporating the use of SCC in structural systems since the early 1990's, whereas Europe has only been using SCC since the mid to late 1990's. The use of SCC within the U.S. has been primarily limited to architectural systems. Despite the limited use, many states have begun to experiment with the use of SCC in their highway bridge construction.

In the U.S. there has been a growing interest in both the precast and prestressed industries in the use and implementation of SCC in many of their commercial products. This appeal is stemmed from the ability of SCC to fill formworks without consolidation and segregation. Unfortunately, there has been no design guidelines set forth to ensure the structural integrity and capacity of structural members that are cast with SCC. This has given rise to a new research frontier aimed at correlating SCC's structural performance and properties with other high performance concretes. This paper explores the effects of transfer lengths for prestressed beams cast with self-consolidating concrete mixtures. Furthermore, the primary objective of this research program is to investigate the length of transfer of prestressed beam specimens cast with self-consolidating concrete, and compare those results with the calculated transfer lengths that are predicted by the ACI and AASHTO transfer length equations.

BACKGROUND

Transfer length, or length of transfer, is an integral component of prestressed concrete members. The transfer length quantifies the distance in which a prestressed strand anchors itself into the concrete allowing for complete transfer of the prestressed force. The structural capacity of prestressed beams derives itself extensively from the axial load and eccentric moment that result from the prestressing operation. Essentially the prestressing strand acts as a stretched rubber band that places an axial stress on the member. Furthermore, depending on the location of prestressing strand in relation to the beam's neutral axis, the eccentric moment will increase the compressive stress within the beam. Fig. 1 illustrates a typical stress arrangement for a prestressed beam.

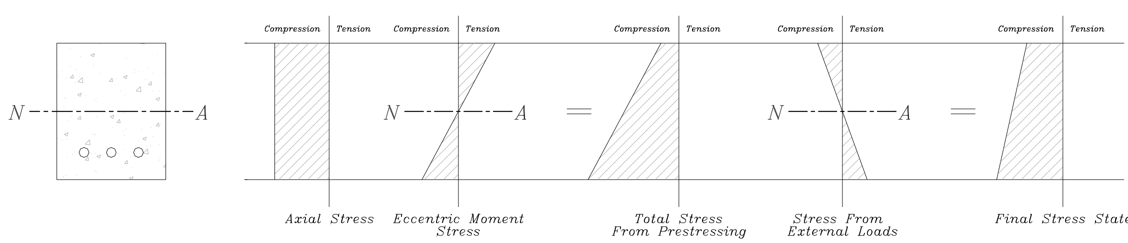

Fig. 1 Typical Stress Arrangement for Prestressed Girders

This stress distribution can only be achieved if the strand is able to anchor itself to the concrete. Without anchorage, the prestressing strand would slip back into the concrete, returning to its unstressed state. Due to the bonding action that takes place within the length of transfer, the stress in the steel is utilized to achieve the beams structural capacity.

Transfer length is defined as the distance, or length of bond, required to transmit the fully effective prestressing force from the strand to the concrete.[2] Transfer length is also commonly stated as the length of bond from the free end of the strand (point of zero stress) to the point at which the prestressing force is fully developed. The resulting region of the beam spanned by this length of bond is referred to as the transfer zone. Over the transfer zone, the tensile stress within the prestressing strand will vary linearly to the point of complete transfer of the prestressing force. There are two transfer zones within a beam, both beginning at either the physical end of the beam or at the termination of any debonding agents. In the area between both transfer zones, the tensile stress within the prestressing strand will remain constant along the length, equal to the effective prestressing stress. Fig. 2 illustrates the relationship of steel stresses with respect to the length of a concrete beam for the transfer length.

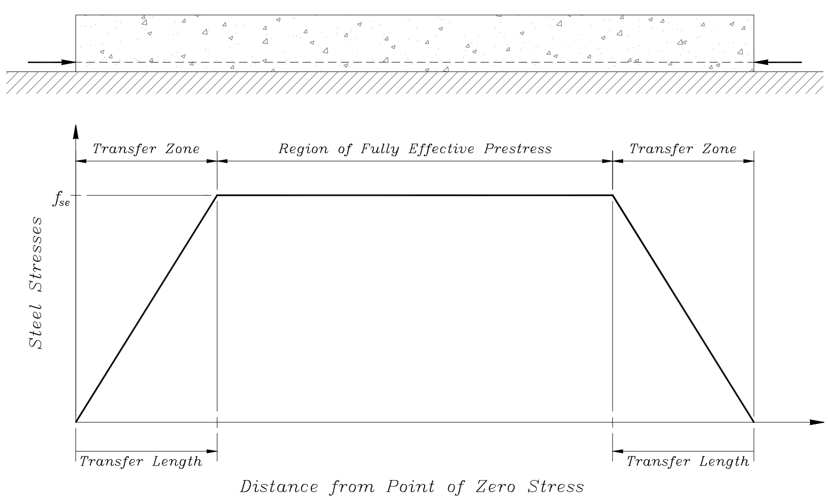

Fig. 2 Idealized Steel Stresses after Release

VARIABLES THAT EFFECT TRANSFER LENGTH

Research since the 1950's has suggested several variables that affect transfer length. Although from one researcher to the next, the significance of many variables differs. Overall it is commonly agreed upon that main variables that directly affect the transfer length are: strand diameter, strand surface condition, concrete strength, and method of release. Ultimately, the amount of prestress force desired governs the length required to transmit that force to the concrete. However, at any given prestress force the transfer length is derived from the unique variables stated above.

Strand diameter has been proven in many research programs to play the most pivotal role in prestress transfer.[2,3] The prestress strand will transfer the prestress force to the concrete over its surface area. Larger strand diameters will have larger surface areas, allowing for more force to be transferred per unit length of the strand. Currently, both ACI[4] and AASHTO[5] use an equation to estimate transfer length that yields proportional increases in length with increases in strand diameter. However, research has shown that this proportionality is not consistent with larger strand diameters.[2] When comparing the amount of force that is developed in a 0.5 versus 0.6 inch diameter strand at an initial prestress of 202.5 ksi, it can be computed that the 0.6 in diameter strand will withstand 44% more force. However, the increase in surface area between a 0.5 and 0.6 inch diameter strand is only 20%. This results in a non-linear increase in transfer length for increases in strand diameter. This phenomenon is only of concern for larger strand diameters.

The effects of strand surface condition on transfer length have also been thoroughly researched. Primarily all the research programs that investigated the effects of strand surface conditions were performed in the mid to late 1950's.[3,6] Testing programs during that time evaluated the use of clean, rusted, and lubricated wires to illustrate differences. According to the research, rusted wires had the best performance in transferring the prestress force in the shortest distance. Both the clean and lubricated wires did not perform as well, and as expected, the lubricated wires were found to have the longest transfer lengths. The performances were attributed to the frictional forces that could be developed by each wire. Since over the transfer zone most of the bond is derived from friction, the wires with higher coefficients of friction had the shortest transfer lengths. This assumption was further analyzed by Cousins, Johnston, and Zia[7] in 1990 with epoxy coated prestressing strands. The epoxy coated strands were found to provide shorter transfer lengths than uncoated equivalents.

Concrete strength has been questioned by many researchers on its importance and affect on prestress transfer. Initial findings suggested that transfer length were only minimally affected by different concrete strengths.[3] For the most part these findings are true. Research performed by Kaar, LaFraugh and Mass[8] in 1963 confirmed these initial findings. They also witnessed that the use of low concrete strengths with large diameter strands would experience slip at release, resulting in larger transfer lengths.

The method of release has been shown over the past decades to have the potential to adversely affect transfer length. There are two primary methods for release in prestress applications. The first is by flame cutting of the fully tensioned strand, and is commonly referred to as sudden release. The method involves the sequential cutting of tensioned strands with a gas torch which leads to violent snapping of the strand back into the concrete. The second method is commonly referred to as gradual release, and involves slower detensioning of the strand by way of a hydraulic ram. The strands are still flame cut; however, the resulting snap back of the strand is less violent. In most cases gradual release has been shown to have shorter transfer lengths and it eliminates eccentric loadings that sometimes result in sudden release.[9]

Initial experimental prestressed SCC research performed by Girgis and Tuan[10] developed several conclusions about the performance of prestressed SCC bridge girders. They found that in some circumstances, transfer lengths for SCC bridge girders could be more than 50% longer than those for girders cast with conventional concrete. Furthermore, the averaged transfer lengths for both of their SCC mixtures were longer than those estimated by ACI and the AASHTO Standard Bridge Specifications. According to Girgis and Tuan, the viscosity modifying admixtures used in SCC may actually weaken the bond between the concrete and prestressing steel. On the other hand, bond tests at 28 days for the SCC mixtures revealed higher bond strengths than that of their conventional concrete. Girgis and Tuan suggested that this may warrant shorter development length requirements for SCC girders.

In a preliminary report of research performed by Burgueno and Haq[11] it is stated that the measured transfer lengths for normally consolidated concrete beams were shorter than those measured for beams cast with three equivalent SCC mixtures. They also mention that despite the longer transfer lengths experienced for the beams cast with the three SCC mixtures, the average transfer length for all three were still within the limits of ACI and AASHTO's recommendations. In the preliminary report Burgueno and Haq fail to report any reason's for their results.

EXPERIMENTAL PROGRAM

The research program consists of casting 18 fully bonded prestressed beams and measuring the transfer length for each of these beams after release. Each beam is 6.5 inches wide and contains two 0.60 inch diameter prestressing strands. The beams also measure 18 feet in length with a height of 12 inches. Two No. 6 Grade 60 rebars were placed with two inches of cover within the compression block of each beam. Quarter inch diameter smooth bar shear stirrups were also provided at 6 inch centers for the entire length of the beam. Fig. 3 shows the detail for beam fabrication.

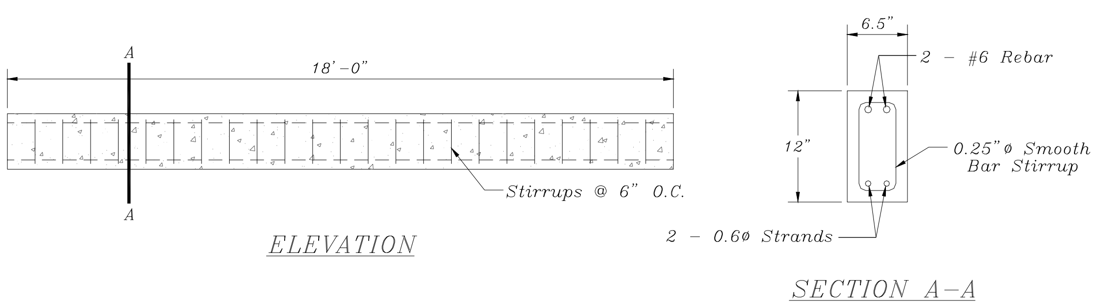

Fig. 3 Typical Beam Specimen Detail

Twelve of the 18 beams were cast with two SCC mixtures, and the remaining 6 were cast using conventional concrete. All three mixtures had targeted initial compressive strengths at release of 7 ksi and 28 day compressive strengths of 12 ksi. The SCC mixtures use proportions similar to those outlined by Khayat.[12] Currently, fabrication and instrumentation of only 12 beam specimens has occurred. These twelve specimens were cast with SCC mixtures made with either Type I or Type III cement. All results presented herein are from these twelve Type I cement and Type III cement SCC beams.

Instrumentation of the beams consisted of Detachable Mechanical Strain Gauge (DEMEC) targets being glued onto the beams. These DEMEC targets were placed along both sides of the beam at the center of gravity of the prestressing steel. The DEMEC points were used in conjunction with a DEMEC gauge to essentially measure the change in length between the target locations. The gauge used to obtain the readings for this research was manufactured by Mayes Instruments Ltd. in the United Kingdom and had a gage length of 200 mm. Readings using the DEMEC system were taken before the prestressing strands were cut, immediately after (within one to two hours) cutting the strands, and at 3, 5, 7, and 14 days of age (No beams have reached 28 days prior to paper submittal). By evaluating the changes in length between DEMEC targets, the concrete strains were calculated. Additionally, using Hooke's law and the modulus of elasticity of the prestressing steel, the change in stress were also computed.

Fig. 4 DEMEC Target Locations

Fig. 5 DEMEC Gauge Reading

FABRICATION OF SPECIMENS

The beam specimens were cast in a prestressing bed constructed on campus at the Engineering Research Center at the University of Arkansas in Fayetteville. This prestressing bed is 50 ft in length allowing for two beams to be stressed at once. The beams were cast with Grade 270 low relaxation seven wire strand. The strand was reported by the manufacturer to have a modulus of elasticity of 28,500 ksi. Upon arrival from the manufacturer, the strand was kept inside to preserve the surface condition provided by the manufacturer. The strand was received with a clean, rust free surface. Prior to casting, the strand was unspooled and cut indoors, then transported less than 50 feet across clean plastic to the prestressing bed where it was tensioned. The strands for each beam were tensioned simultaneously to 75% of f_{pu}, or 202.5 ksi. This was achieved by using two hydraulic rams in parallel to push a steel block to which the strands were anchored (See Fig. 6 and Fig. 7 for an illustration of the tensioning device used and prestressing abutment). The strands were tensioned until a predetermined elongation that accounted for 4.5 inches of elastic elongation of the strand, as well as 3/8 of an inch to account for chuck seating at each end of the strand. A hydraulic pressure gauge was also used to verify the tensioning procedure.

Fig. 6 Tensioning Device

Fig. 7 Prestressing Abutment

The concrete mixture used for the Type I cement beams was designed to be a high-strength self-consolidating concrete mixture. The target release strength of the mixture was 7,000 psi and the target 28 day strength was 12,000 psi. The maximum aggregate size used was half inch to improve flowability of the mix and accommodate the cross-section of the beams. In order to achieve the flowability requirements, the Type I SCC mixture also utilized high range water reducers and viscosity modifying admixtures. Three different chemical admixtures were used in the SCC mixtures, which were ADVA 170, ADVA 555, and VMAR – 3. ADVA 170 is a high-range water reducer suggested by its manufacturer for low water cement ratio concretes. ADVA 555 on the other hand is a combination of high-range water reducer and viscosity modifying admixture suggested by its manufacturer specifically for SCC applications. VMAR – 3 is a viscosity modifying admixture that is suggested by its manufacturer for SCC applications also. Extensive laboratory test batching was performed prior to beam casting to develop a reliable and stable Type I SCC mixture. The selected mix design (which is detailed in Table 1) was used to cast all Type I cement SCC beams. Each beam was cast with two separate batches, with the exception of beams SCC I – 1 & 2 which were cast in three batches, due to size of the laboratory mixer. Table 2 lists the fresh concrete properties and cylinder strengths for all Type I SCC batches.

Table 1. Mix Designs for Type I and Type III SCC mixtures

Materials	Type I SCC	Type III SCC
Batch Size (cu. ft.)	8	8
Cement (lb/yd^3)	950	808
Fly Ash (lb/yd^3)	0	142
Coarse Aggregate (lb/yd^3)	1350	1350
Fine Aggregate (lb/yd^3)	1474	1400
Water (lb/yd^3)	285	304
Water/Cement Ratio	0.30	0.32
ADVA 170 (fl. oz/cwt)	7.8 – 14.5[a]	8 - 9[a]
ADVA 555 (fl. oz/cwt)	0 - 3[a]	0
VMAR-3 (fl. oz/cu. yd)	0 – 30.4[a]	0 – 30.4[a]

Note: 1 lb. = 0.454 kg; 1 oz = 29.57 ml
[a] Dosages of admixtures varied due to variations in ambient air temperatures during time of batching for individual mixes.

Table 2. Fresh and Hardenrd Concrete Properties for Type I SCC Mixtures

Mixture ID (1)	Beams Casted (2)	Fresh Concrete Properties: Slump Flow (in.) (3)	T20 (sec) (4)	VSI (5)	Concrete Strengths: f'_{ci} (psi) (6)	7 Day (psi) (7)
SCC I – 1 – M1	SCC I – 1	26.0	4.0	1.0	8,520	12,480
SCC I – 1 – M2		26.0	3.0	1.0		
SCC I – 1 – M3		27.0	4.0	0.5		
SCC I – 2 – M1	SCC I – 2	30.0	3.0	0.5	8,700	13,360
SCC I – 2 – M2		25.0	4.0	1.0		
SCC I – 2 – M3		24.0	3.4	1.0		
SCC I – 3 – M1	SCC I – 3	27.5	2.8	1.5	7,220	10,680
SCC I – 3 – M2		30.0	2.0	1.5		
SCC I – 4 – M1	SCC I – 4[a]	30.0	2.0	1.5	5,900	9,590
SCC I – 4 – M2		28.0	2.8	0.5		
SCC I – 5 – M1	SCC I – 5	30.0	2.6	---[b]	7,430	9,710
SCC I – 5 – M2		31.0	2.2	---[b]		
SCC I – 6 – M1	SCC I – 6	28.5	3.3	---[b]	7,330	10,290
SCC I – 6 – M2		27.0	2.8	---[b]		
SCC I – 7 – M1	SCC I – 7	27.0	3.9	0.5	8,450	9,500
SCC I – 7 – M2		25.5	4.2	0.5		
SCC I – 8 – M1	SCC I – 8	29.5	4.6	1.5	8,550	11,890
SCC I – 8 – M2		29.0	2.5	0.5		

Note: 1 in. = 25.4 mm; 1 psi = 6.895 kPa.
[a] The concrete strengths for Beam SCC I – 4 are lower due to an accidental increase in water-to-cement ratio.
[b] VSI Data is missing for these beam specimens

In addition to the Type I SCC mixture, a similar SCC mixture using Type III cement was used to cast an additional 6 beams. Currently, fabrication of only four of the six beams has been accomplished. Similar to the Type I SCC mixture, the Type III SCC mixture has a target release strength of 7,000 psi and 28 day strength of 12,000 psi. Additionally, the Type III SCC mixture contains the same amount and size of coarse aggregate as the Type I SCC mixture. The mix design for the Type III SCC mixture can be found in Table 1, and the fresh concrete properties and cylinder breaks for all beams cast with Type III SCC mixture are provided in Table 3.

Table 3. Fresh and Harden Concrete Properties for Type III SCC Mixtures

Mixture ID (1)	Beams Casted (2)	Fresh Concrete Properties: Slump Flow (in.) (3)	T20 (sec) (4)	VSI (5)	Concrete Strengths: f'_{ci} (psi) (6)	7 Day (psi) (7)
SCC III – 1 – M1	SCC III – 1	28.5	1.9	0.5	7,080	9,740
SCC III – 1 – M2		27.5	1.3	0.5		
SCC III – 2 – M1	SCC III – 2	26.0	1.6	0.5	6,880	9,640
SCC III – 2 – M2		25.0	1.9	0.5		
SCC III – 3 – M1	SCC III – 3	29.0	1.9	1.0	7,080	8,990
SCC III – 3 – M2		25.5	1.9	0.5		
SCC III – 4 – M1	SCC III – 4	26.5	2.4	1.0	7,450	9,840
SCC III – 4 – M2		29.0	2.5	0.5		

Note: 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

Each beam specimen for both the Type I and Type III SCC testing series were cast using two mixes. This was done due to the limited size of the laboratory mixer. Initially, the first mix batched would be placed into the formwork after the strands were tensioned. This mix would on average fill the formwork from end to end to a depth of 7 inches. This ensured that all the concrete within the localized area of influence for both of the strands would have the same concrete properties. Immediately after the first mix was emptied out of the mixer, the second mix for each beam specimen would be batched and placed in the form. The time between the final pouring of the first mix to initial pouring of the second mix into the formwork was within 45 minutes for all specimens. Additionally, limited internal vibration was used in some instances in which ambient air temperatures would cause the top layer of the first mix within the formwork to form a thin crust. This procedure would ensure that both mix 1 and mix 2 for the beam specimen would be thoroughly mixed, and protect against the formation of cold joints within the beam.

Each beam specimen was allowed to cure uncovered for 1 day within the formwork until the mixtures achieved the target release strengths. Once the initial readings were taken and the concrete had reached the desired strength, the strands were released gradually. Each gradual release was accomplished by slowly relieving the pressure simultaneously in each of the hydraulic rams used during the tensioning process. During release, the beam specimens would slowly slide along the prestressing bed toward the dead end (opposite end from the tensioning device). Since the prestressing bed could accommodate two beams in a line, there was enough frictional force developed during release to keep the exposed segments of strand, between each beam and between the beam and dead end abutment, to remain taut. These sections of strand were flame cut with an acetylene torch. Cutting of these sections did not result in any dramatic snapping of the strand. In all cases the heated area of the strand would yield enough to relieve the remaining tension in the strand.

Fig. 7 Prestressing Bed

Fig. 8 Beam Formwork

DATA ANALYSIS

Transfer lengths for all beam specimens were obtained by interpreting the concrete surface strain profiles. These surface strain profiles were generated from the data recorded from the DEMEC gauge readings. Initial DEMEC readings prior to release were used as the initial reference for all subsequent readings at 1, 3, 5, 7, and 14 days. The strain profiles were generated by subtracting the difference between DEMEC readings, and then multiplying that difference by a calibrated factor provided by the instruments manufacturer. These values were then graphed with respect to its location along the length of the beam (See Fig. 9 for a typical surface strain profile). Since DEMEC readings were obtained from both sides of each beam specimen, an average strain profile was developed. These averaged strain profiles were then refined (using the 95% average maximum strain method) and used to interpret the measured transfer lengths for all beam specimens.

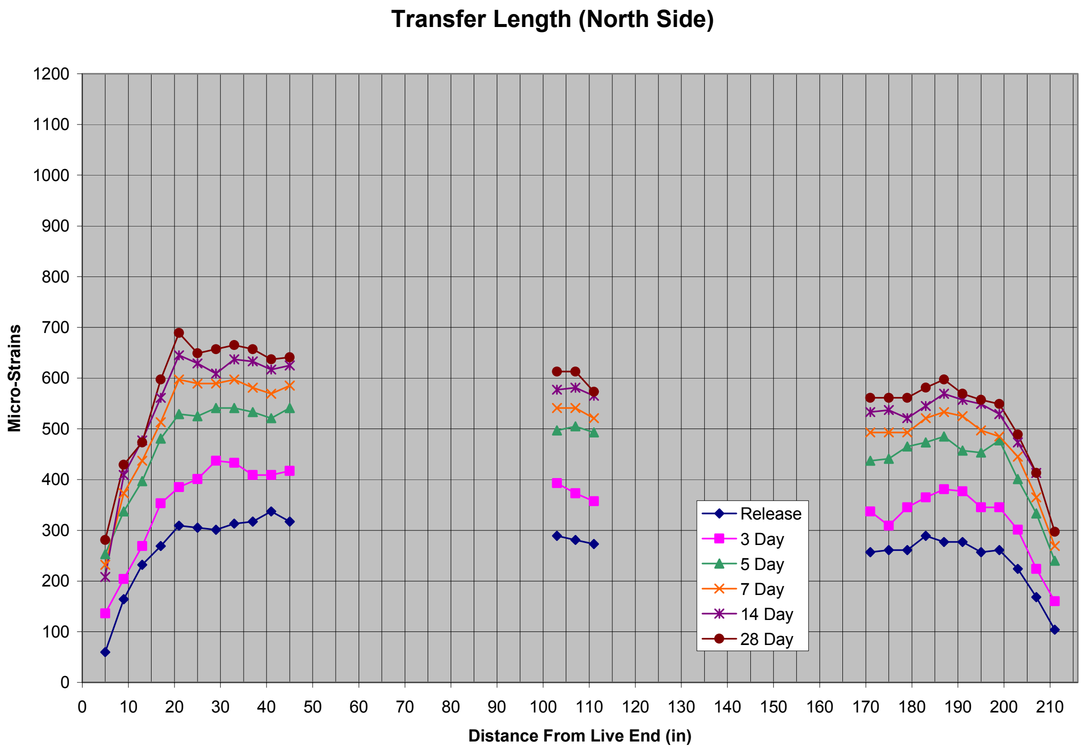

Fig. 9 Strain Profile for Beam SCC I – 5

In order to eliminate arbitrary interpretations of the strain profiles for the measured transfer lengths, the 95% AMS method discussed by Russell and Burns [9] was employed. This method first numerically averages the strain at any DEMEC point with the corresponding strains immediately adjacent to that point. These new strains are again plotted with respect to its location along the length of the beam. Using this new strain profile (which is referred to as a smoothed strain profile), all strains within the strain plateau are averaged to determine the average maximum strain. This value is then multiplied by 0.95 and a line is constructed on the strain profile that is equal to this value. Transfer length is determined to be the length at which the 95% AMS line intersects with the smoothed strain profile. This procedure is illustrated for the 14 day smoothed strain profile in Fig. 10.

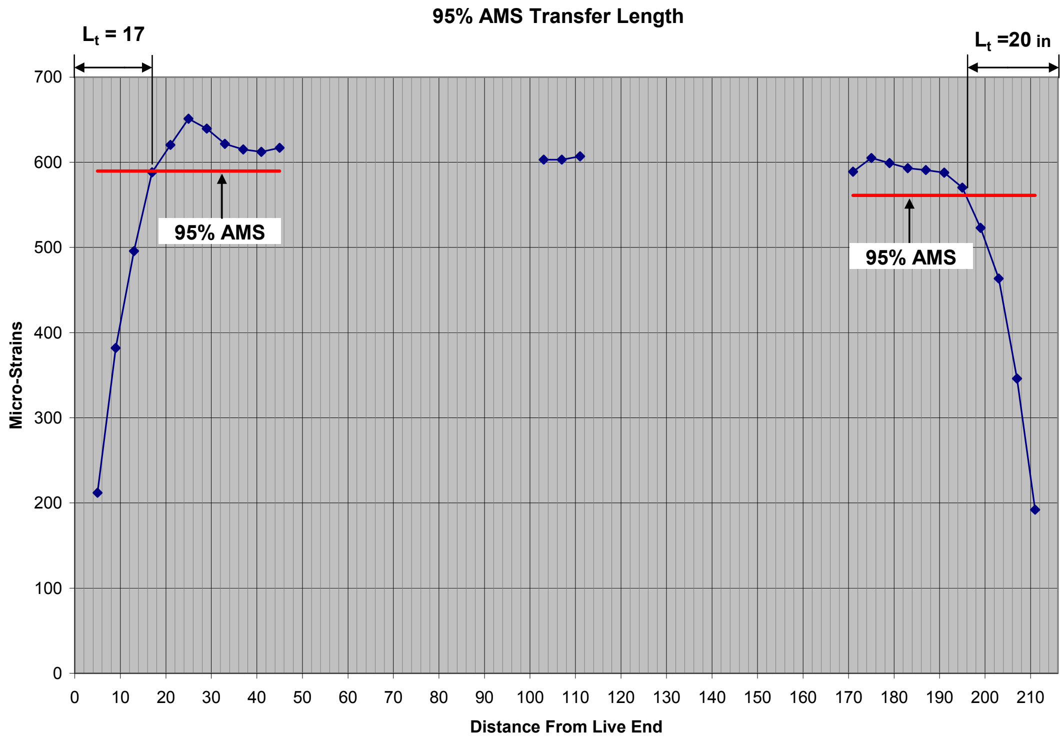

Fig. 10 95%AMS Strain Profile for Beam SCC I – 3

MEASURED TRANSFER LENGTHS

Transfer lengths were measured for all beams presented using the previously described 95% AMS method. Results for the SCC beams cast with Type I cement are presented in Table 4. The transfer lengths reported in this table correspond to 14 day data with the exception of beams SCC I – 7 and SCC I - 8. Statistical analysis of this data reveals that the average transfer length for the Live End of all Type I cement SCC beams was equal to 20.7 inches with a standard deviation of 3.7 inches. Similarly, the average transfer length for the Dead End for all Type I cement SCC beams was equal to 21.5 inches with a standard deviation of 3.4 inches.

Table 4. Measured Transfer Lengths for SCC I Beam Series

Beams Specimen	Measured Transfer lengths (in.)	
	Live End	Dead End
SCC I – 1	24	26
SCC I – 2	25	--- [a]
SCC I – 3	17	20
SCC I – 4	22	22
SCC I – 5	20	18
SCC I – 6	16	16[b]
SCC I – 7	20[c]	21[c]
SCC I – 8	19[c]	17[c]
Average 14 Day Transfer Length	20.7[d] (σ = 3.7)	21.5[d] (σ = 3.4)

Note: 1 in. = 25.4 mm
[a] Transfer length data for this specimen was very erratic.
[b] Several DEMEC targets were lost on one side of Beam SCC I – 6 at the Dead End; therefore the reported transfer length is only based on DEMEC data from one side.
[c] Both SCC I – 7 and SCC I – 8 measured transfer lengths correspond to 7 day readings.
[d] Average Transfer Lengths are for beams with 14 day data only.

Table 5 reports the measured transfer lengths for all SCC Beams cast with Type III cement. The data presented in Table 5 reports 7 and 14 day data for beams SCC III – 1 & 2, and 7 day data for beams SCC III – 3 & 4. Statistical analysis of the 7 day data reveals average Live End transfer length for Type III cement SCC beams is 18.7 inches with a standard deviation of 2.5 inches. Similarly, the average Dead End transfer length for all Type III cement SCC beams is equal to 20.0 inches with a standard deviation of 2.8 inches.

Table 5. Measured Transfer Lengths for SCC III Beam Series

Beams Specimen	Measured Transfer lengths (in.)			
	Live End		Dead End	
	7 Day	14 Day	7 Day	14 Day
SCC III – 1	19	19	18	18
SCC III – 2	21	21	22	21
SCC III – 3	16	---	16	---
SCC III – 4	18	---	17	---
Average 7 Day Transfer Length	18.7 (σ = 2.5)		20.0 (σ = 2.8)	

Note: 1 in. = 25.4 mm
--- No transfer length data has been obtained prior to submittal.

ANALYSIS OF RESULTS

Currently the results from both series of test specimens show transfer lengths to be within those estimated by ACI and AASHTO equations. The computed value for the ACI and AASHTO equations are presented with a comparison to the measured transfer lengths in Tables 6 and 7 for SCC I beam series and SCC III beam series, respectively. The value of f_{se} for each beam was determined using an effective prestress force that was based on measured losses for each beam. Current results illustrate transfer lengths for all SCC beam specimens that are 60% below the predicted transfer length value using the ACI and AASHTO's equations. It should be noted that the measured transfer lengths for all specimens correspond to a gradual release procedure. It is expected that the transfer lengths for members that are detensioned suddenly by flame cutting would likely experience longer transfer lengths than reported here. These transfer lengths could even approach or surpass the conservative calculated value for transfer length as prescribed by the ACI and AASHTO equations.

Table 6. 14 Day Transfer Length Data for SCC I Beam Series

Beam Specimen	f_{se} (ksi)	Transfer Lengths (in.)					$\frac{Measured}{(f_{se}/3)d_b}$	
		Measured		ACI/AASHTO $(f_{se}/3)d_b$	ACI $50d_b$	AASHTO $60d_b$		
		Live End	Dead End				Live End	Dead End
SCC I - 1	177.8	24.0	26.0	35.6	30.0	36.0	0.67	0.73
SCC I - 2	177.4	25.0	--- [a]	35.5	30.0	36.0	0.70	---
SCC I - 3	185.2	17.0	20.0	37.0	30.0	36.0	0.46	0.54
SCC I - 4	181.4	22.0	22.0	36.3	30.0	36.0	0.61	0.61
SCC I - 5	183.6	20.0	18.0	36.7	30.0	36.0	0.54	0.49
SCC I - 6	182.9	16.0	16.0[b]	36.6	30.0	36.0	0.44	0.44
Average		20.7	20.4	36.3			0.57	0.56

Note: 1 in. = 25.4 mm

[a] Transfer length data for this specimen was very erratic.

[b] Several DEMEC targets were lost on one side of Beam SCC I – 6 at the Dead End; therefore the reported transfer length is only based on DEMEC data from one side.

Table 7. 7 Day Transfer Length Data for SCC III Beam Series

Beam Specimen	f_{se} (ksi)	Transfer Lengths (in.)					$\frac{Measured}{(f_{se}/3)d_b}$	
		Measured		ACI/AASHTO $(f_{se}/3)d_b$	ACI $50d_b$	AASHTO $60d_b$		
		Live End	Dead End				Live End	Dead End
SCC III – 1	179.9	19.0	18.0	36.0	30.0	36.0	0.53	0.50
SCC III - 2	179.7	21.0	22.0	35.9	30.0	36.0	0.58	0.61
SCC III - 3	184.1	16.0	16.0	36.8	30.0	36.0	0.43	0.43
SCC III- 4	183.9	18.0	17.0	36.8	30.0	36.0	0.49	0.46
Average		18.5	18.3	36.4			0.51	0.50

Note: 1 in. = 25.4 mm

It has been seen in the early stages of transfer length growth that beam specimens cast with viscosity modifying admixtures did experience slightly longer transfer lengths than those cast with SCC proportioned without VMA. On average, beams cast with VMA experienced transfer lengths 10 to 20% greater than those measured for beams cast without VMA. These results mimic the suggestions from Girgis and Tuan's[10] research of prestressed bridge girders cast with SCC mixtures. They suggest that VMA may have an adverse affect on early age bond strength between the prestressing strand and the concrete. The results showing the effect of VMA on transfer length are shown in Tables 8 and 9.

Table 8. Live End VMA Effects

Day	Average Measured Transfer Length (in.)		$\frac{VMA}{NonVMA}$
	Beams Cast without VMA	Beams Cast With VMA	
Release	18.0	22.0	1.22
3	18.7	22.0	1.18
7	18.7	21.7	1.16
Average	18.4	21.9	1.19 (σ = 0.03)

Note: 1 in. = 25.4 mm
Sample size is 6 beams, three of which were cast with VMA and three that contained no VMA. Other than VMA, mixture proportions were identical for the six beams.

Table 9. Dead End VMA Effects

Day	Average Measured Transfer Length (in.)		$\frac{VMA}{NonVMA}$
	Beams Cast without VMA	Beams Cast With VMA	
Release	18.8	21.0	1.12
3	18.3	19.5	1.06
7	19.3	20.5	1.06
Average	18.8	20.3	1.08 (σ = 0.03)

Note: 1 in. = 25.4 mm
Sample size is 6 beams, three of which were cast with VMA and three that contained no VMA. Other than VMA, mixture proportions were identical for the six beams.

Achieving target release strengths proved to be difficult for the SCC I beam series due to large variations in outdoor ambient air temperature where the beams were cured. All beams were cast during the summer months where temperatures range from the low 80's to 100°F. These variations in temperature resulted in higher compressive strengths at one day of age when the temperatures approached 100 F and lower strengths at 80 F. Release strengths were determined from test cylinders that were cast during batching. The cylinders were cured with the beams.

The average release strength for the SCC I beams series was also compared to that of the SCC III beam series. The average release strength for all SCC I beams was 7,760 psi with a standard deviation of 970 psi. Similarly, the computed average for all SCC III beams was 7,120 psi with a standard deviation of 240 psi. It can be seen that the SCC I beams on average had a higher compressive strength at release than the SCC III beams; however, average transfer length data at release for both series of specimens reveals that the SCC I beam series has a longer transfer length than its SCC III counterparts.

CONCLUSIONS

The goal of this research program was to correlate measured transfer lengths for two SCC mixtures to the transfer length provided by the ACI and AASHTO transfer length equations. The measured transfer length data were obtained by analyzing concrete surface strain profiles for SCC beam specimens that were gradually released. Results from this investigation have allowed the following conclusions to be drawn:

- 14 day data suggests that transfer lengths for Type I cement SCC's are shorter than the ACI and AASHTO's predicted length to ensure adequate flexural resistance. This data shows the measured transfer lengths to be approximately 60% of that predicted by the ACI and AASHTO equations.
- 7 day data for the Type III cement SCC's suggests that the transfer lengths are also shorter than the maximum expected length of transfer as specified by ACI and AASHTO to ensure adequate flexural resistance. The available data shows these measured transfer lengths to be around 50% of ACI and AASHTO's predicted lengths.
- Preliminary analysis of the available transfer length data for the SCC I beam series supports the findings from Girgis and Tuan research program, which state that viscosity modifying admixtures may adversely affect early age bond strengths. This has been seen in the analysis of the transfer length data, where on average, transfer lengths are 13% higher for beams cast with VMA's. Additional bond tests should be performed to obtain a stronger validation of this phenomenon.
- Variations in release strengths have shown in the SCC I beam series to play an insignificant role on release transfer lengths. It should be noted that this suggestion may only be valid over a finite range of release strength (6,000 psi to 9,000 psi) that is similar to those reported here.
- Despite having a higher average release strength, SCC I beams series have longer transfer lengths than the SCC III beam series which have lower compressive strengths at release.

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