PERFORMANCE OF PRECAST/PRESTRESSED DOUBLE-TEES CAST WITH LIGHTWEIGHT SCC

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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 widely accepted and used in the precast industry. The use of lightweight SCC is becoming more common due to increasing transportation costs. This current research program is examining the performance of two full size, precast/prestressed double tees cast with lightweight SCC. Each double tee was instrumented with 4 vibrating wire strain gauges at midspan. The strains were monitored continuously while the double tees were in the precast plant's yard and then periodically monitored once erected. Additionally, the initial camber and camber growth of the double tees were measured. The lightweight SCC used in the double tees had a slump flow of approximately 31 inches and a VSI of 1.5. The concrete strength was 3970 psi at release and 6980 psi at 28 days, and the 28 day modulus of elasticity was 3400 ksi. Finally, transfer and development length of laboratory beams cast with the same lightweight SCC mixture will also be measured. The measured prestress losses, transfer and development lengths, and camber will be compared to values obtained using standard prediction equations.

Keywords: LWSCC, SCC, Prestress Losses, Camber, Transfer Length, Development Length, Double-Tees

INTRODUCTION

The use of self-consolidating concrete (SCC) has increased in popularity in the prestressed/precast industry over the past several years. Currently, there are difficulties estimating camber in SCC beams. Often, the amount of camber estimated in the design process and the amount of camber measured in the field during construction vary considerably. This can lead to installation problems. The girders/beams may not match up at the haunches, and adjustments either to the slab or haunches are necessary in order to install the girders. As expected, these difficulties in the construction process can be expensive and time consuming, delaying construction. Additionally, the lack of performance data on SCC girders has prompted some states to disallow the use of SCC in bridge girders[12]. This includes lack of performance data on elastic modulus, camber, prestress losses, and bond. Many of these performance properties considered require special care. Concerns over strength properties may be handled by incorporating factors of safety to ensure adequate capacity. Serviceability and prestress losses, however, must be calculated more accurately to ensure proper design. In addition to the need for accurately estimating prestress losses and camber, there is a need to determine other performance properties. Transfer and development length are also important to evaluate and will be considered in this research program.

Lightweight self-consolidating concrete (LWSCC), a relatively new type of SCC, has had very few studies conducted on its performance. The use of LWSCC has two distinct benefits over conventional high performance concrete (HPC). The reduced weight of the LWSCC can provide lower transportation costs in a time of greatly increased fuel prices. Additionally, the LWSCC may be placed with less labor and effort as compared to conventionally vibrated concrete. While LWSCC has great potential for increased use in the future, it is important to conduct research to determine its properties and behavior.

The main objective of this paper is to report findings on two full sized precast/prestressed double-tees cast with LWSCC and to compare measured values of properties such as elastic modulus, prestress losses, and camber to traditional prediction methods. This research program will be one of the first to measure these properties in LWSCC members.

BACKGROUND

SCC was originally developed at the University of Tokyo, Japan, in the 1980s. SCC has many advantages over conventional concrete, including easy placement in thin-walled elements and the ability to compact itself under its own weight without vibration[8]. There may also be a cost savings benefit due to the reduced amount of labor and equipment needed because of the ease of placement. There is also reduced noise and vibration during placement[4].

SCC is produced with readily available materials. Although essentially the same components are used for conventional concrete as for SCC, the mixture proportions vary somewhat. SCC uses a larger amount of fine aggregate while incorporating a smaller amount of coarse aggregates. SCC may also use more filler materials such as "fly ash, limestone powder, blast furnace slag, silica fume and quartzite powder[8]." SCC allows for a low water to cementitious material ratio (w/cm), and it allows for a high degree of flowability. Typically, the w/cm for SCC is less than 0.40. The combination of low w/cm and flowability is due to the high range water reducers (HRWR) incorporated into the mix. Typically, the dosage rate of HRWR ranges from 0.5% to 2.0% of the weight of the cement in the mix[4].

SCC can be pumped through an opening in the bottom of forms, or it can be conventionally placed from the top of forms. Tests on SCC have proven it to be fairly homogeneous. SCC has an additional advantage in that it moves through intricate formwork without segregation or bleeding[4]. These benefits make SCC very appealing to the precast/prestressed concrete industry.

The most significant difference between SCC and conventional concrete is its behavior while fresh. SCC has a unique rheology. It has a particularly low yield stress, which "corresponds to the minimum shear stress required to initiate flow[1]." The slump flow of SCC is used to describe the mixture's filling ability. Instead of measuring the slump vertically, as is the case for conventional concrete, slump flow is measured horizontally. ACI Committee 237 recommends that the slump flow should not be less than 22 inches for an application with a high level of reinforcement. Another quality of well-designed SCC is high passing ability. This refers to how well the concrete can move around obstacles and narrow spaces without blockage. Additionally, a well designed SCC mixture will exhibit stability. A stable mixture will remain homogeneous during its flow and setting[1]. Hardened properties of SCC follow trends similar to conventional concrete, while some properties may be different due to different mixture proportions and different materials used in SCC.

LWSCC provides additional advantages by lowering the self-weight of the member which in turn may lead to significant reductions in transportation costs as well as a reduction in dead load acting on the structure. Precast yards are often able to include an additional beam cast with LWSCC on one truck compared to normal weight concrete while staying under highway load limits.

EXPERIMENTAL PROGRAM

The first phase of the experimental program included instrumenting and monitoring two full-scale double-tee beams. Both double-tees were cast using LWSCC at Coreslab Structures, a precast plant in Conway, Arkansas. The first double-tee is 31' 10 ¾" long and is designated as DT-32 in this paper (32 referring to approximate length in feet). The second double, tee, designated T-59, is 58' 7" long. The beams each contained ten ½ in.

diameter Grade 270 prestressing strands. The following diagrams show cross-sections of the researched beams. The components of the LWSCC include cement (with no mineral admixture replacement), expanded clay lightweight aggregate, sand, a high-range water reducer (HRWR), and an air entraining agent (AEA). Table 1 shows the mixture proportions for the LWSCC mixture.

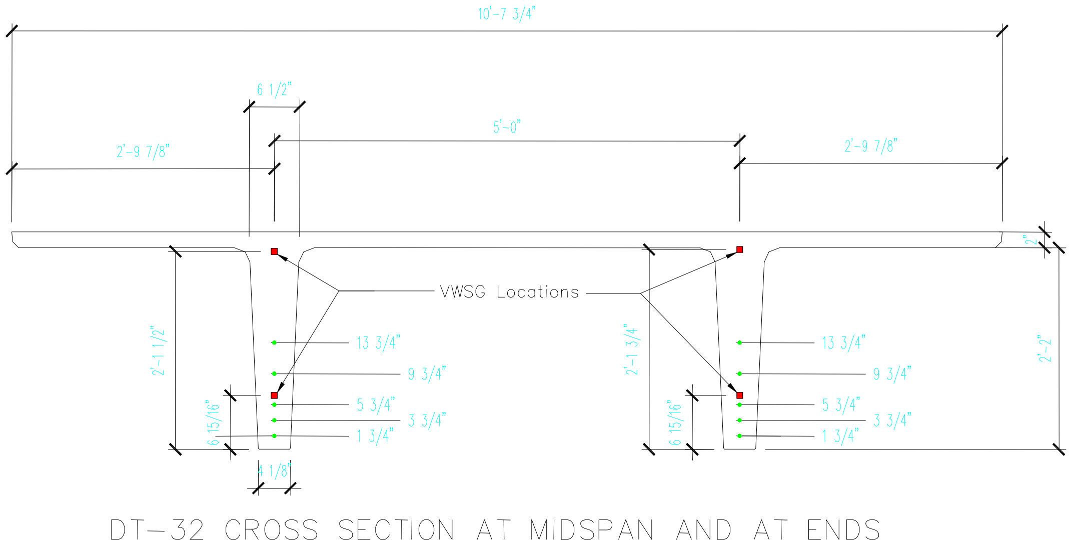

Figure 1: Diagram of a cross section of beam DT-32 including locations of VWSGs

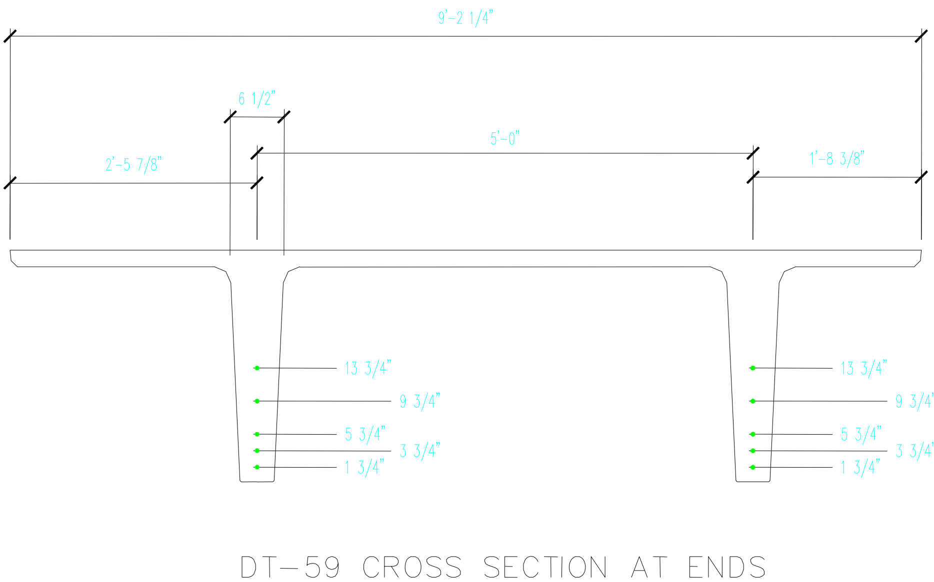

Figure 2: Diagram of a cross section at an end of beam DT-59

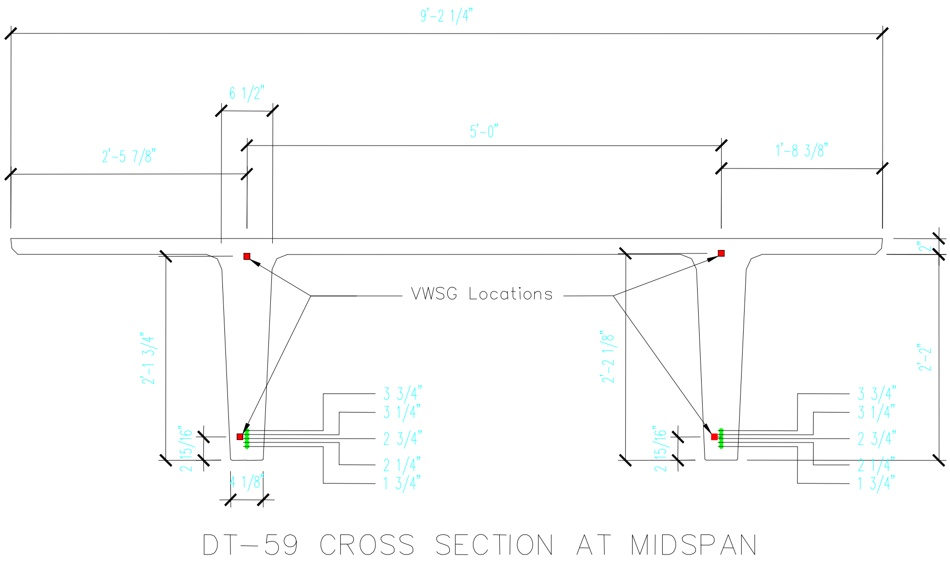

Figure 3: Diagram of a cross section at midspan of DT-59

Table 1: Mixture proportions of LWSCC evaluated

Material	Weight (lb)	Volume (cf)
Cement	795	4.04
Water	302	4.84
Lightweight Agg.	743	9.16
Sand	1292	7.87
Air Content	4	1.08
AEA (AE-90)		0.3 oz/cwt
HRWR (PS-1466)		7.5 oz/cwt
w/c		0.38
Calculated Unit Weight		116.02

PRODUCTION PROCESS

The production process began by tensioning each strand to 26.9 kips. This value corresponds to 175.8 ksi (65.1% of f_{pu}). The forms were lubricated to aid in removal from forms after transfer. Additional non prestressed reinforcement was added. DT-58 had its strands depressed at midspan. VWSGs were placed within the beam after tensioning but before depression of strands. The LWSCC was batched on site and transported by front unloading rotary drum mixer trucks. Slump flow, unit weight, and air content tests were run and test results recorded. Concrete was placed in the forms between 5:00 pm and 5:30 pm on November 13, 2007. The concrete was placed and allowed to fill each stem and then to fill the flange. Workers lightly vibrated the concrete deposited in the stems. Additionally, a vibrating mechanical screed was used to finish the surface. The beams were to receive a topping slab later, so the surface was left rough.

Several beams were cast at the same time on the same bed. After completion of finishing, a tarp was rolled over the beams to prevent moisture loss. Beginning 11 hours after placement, cylinders were tested in compression to determine when the compressive strength was greater than the specified stripping strength of 3750 psi. The mix achieved 3968 psi 17 hours after placement. Shortly afterwards, the tarp was removed from the top of the double-tees.

Before transfer, the depression arms and frames were removed. Nineteen hours after placement, the transfer process began by cutting the same strand at each end of the bed at the same time. After the strands were cut on the ends, each individual beam was released separately using the same releasing pattern as on the bed ends. After transfer, the beams were transferred by walking crane to a temporary storage area where the beams underwent inspections. One day later, the beams were transferred to the storage yard where they remained until they were taken by truck to the construction site.

MEASUREMENTS

Several objective measurements were conducted in this research program. Both fresh and hardened properties were measured and recorded. Fresh properties measured include slump flow, unit weight, and air content. Slump flow was conducted according to ASTM C 1611, and unit weight was conducted according to ASTM C 138. Since lightweight aggregate was used in the concrete mix, air content was measured by the volumetric method (roll-o-meter) according to ASTM C 173.

Compressive strength and elastic modulus were measured on companion cylinders made from a diverted stream during the placement of the DTs. Compressive strength was tested at 11 hours, 16 hours (transfer), 7 days, 28 days, and 90 days. Elastic modulus was measured at 7, 28, and 90 days.

Both double-tees were instrumented with four Geokon® Model 4200 vibrating wire strain gauges (VWSGs) each. VWSGs were put at or near the center of gravity of the prestressing steel (c.g.s) and at the location where the stems meet the flange. See figures 1-3. The strain gauges in the stems of DT-32 were placed at the center of gravity 6.95” from the bottom between the 3rd and 4th prestressing strands from the bottom. Since DT-59 had its strands depressed at midspan, the VWSGs were secured to the side of the 3rd strand from the bottom and were offset 2’ from midspan to avoid damage from the depression equipment. The angle of the strand from end to midspan led to a 0.21” difference in height between the c.g.s. and the location of the VWSGs. Corrections for this difference in height of VWSG to c.g.s were accounted for by using the strain measurements from the top gauges and using the linear strain distribution to calculate actual strain at the c.g.s. Measurements were taken before and after placement of concrete using a handheld reader (Geokon® GK-401 Readout Box). After the tarp was rolled out over the beams, all eight VWSGs were connected to a data acquisition system (DAS). Both temperature and strain were measured at three minute intervals continuously until shortly after transfer. After movement to the temporary storage location, the DAS recorded strain and temperature data at 15 minute intervals. The DAS was disconnected before movement of the beam and reconnected after movement.

Figure 4: Apparatus and setup to measure elastic modulus of concrete cylinders

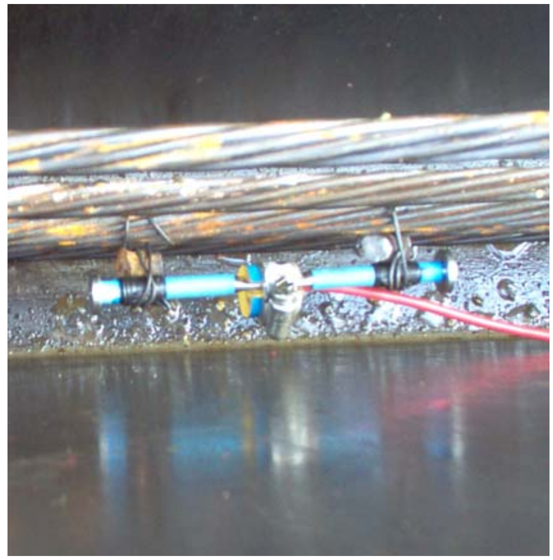

Figure 5: Photograph of installed VWSG attached to a prestressing strand (before depression)

Camber was also measured at various times. Camber was measured using an automatic level and an engineer's scale clamped to a surveying rod. Three marks were made on the top surface of each double-tee including one 4 inches from each end and one near the midspan. A mark was made at the measured center of DT-32. The center mark had to be offset 6.5" from center on DT-59 in order to take measurements for the baseline conditions before the depression frame was removed. Relative elevations were measured at each mark on the beam (one at each end and one at midspan). The midspan camber was equal to the relative difference in height at midspan relative to an imaginary line between the two endpoints. Camber measurements were first made before the depression frame was removed and before any strands were cut. Camber was again measured after the strands at the ends of the prestressing bed were cut and again after each of the two individual beams were cut free. Additionally, camber measurements were made before and after each move around the plant yard.

RESULTS

FRESH PROPERTIES

Fresh properties were measured during the placement of the double-tee beams. The following table shows a summary of measured fresh properties. The roundness of the lightweight aggregate combined with the moisture included and high range water reducer added helped lead to a high slump flow of 31 inches.

Table 2: Measured fresh properties of LWSCC

Measured Fresh propeties	
Slump flow (in)	31
VSI	1.5
Unit Weight (pcf)	120
Air Content (%)	0.5

COMPRESSIVE STRENGTH

The LWSCC exhibited normal strength gains. Figure 6 shows the strengths measured prior to release, at 7 days, at 28 days, and at 90 days for the mixtures contained in DT-32 and DT-59. Compressive strength values displayed are moist-cured strengths. Air-cured strengths are also displayed at 28 days.

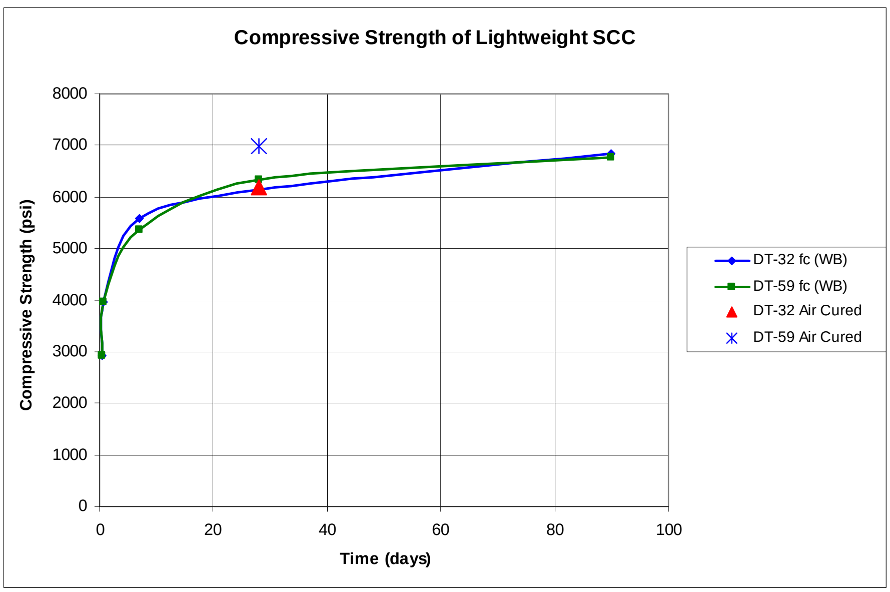

Figure 6: Chart displaying strength of moist-cured LWSCC cylinders

MODULUS OF ELASTICITY

Modulus of elasticity tests were performed on companion cylinders cured in a water bath. The measured results were compared against prediction equations found in AASHTO LRFD Bridge Design Specifications[3] (2007) and ACI 318-05 equation[2]. Table 3 shows results of modulus of elasticity tests. As can be seen in Table 3, the prediction equations represent the measured value fairly accurately. Figure 7 shows a graphical comparison of measured elastic moduli values versus the AASHTO-LRFD and ACI 318 prediction equations.

Table 3: Measured and predicted values of elastic modulus

Beam	Time (days)	Measured MOE (ksi)	Predicted MOE (ksi)	Predicted/ Measured
DT-32	7	3108	3240	1.04
	28	3580	3396	0.95
	90	3935	3590	0.91
DT-59	7	3341	3178	0.95
	28	3376	3449	1.02
	90	4099	3567	0.87

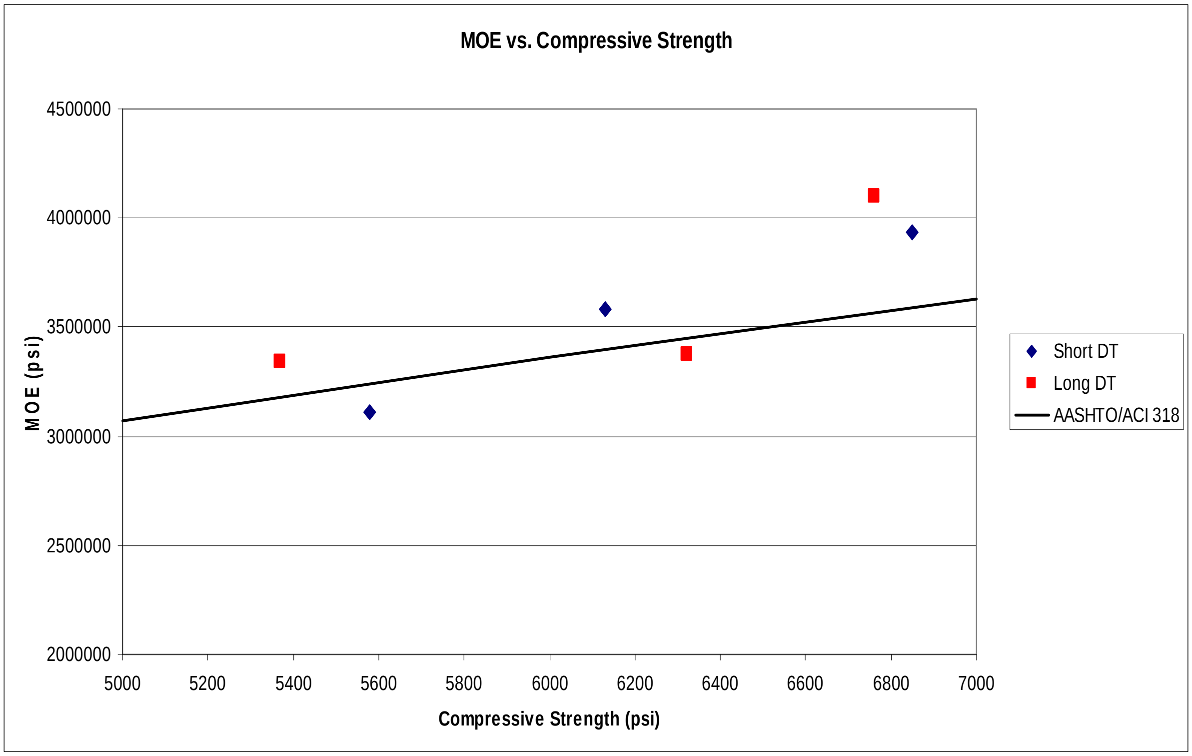

Figure 7: Graphical representation of measured MOE values of companion cylinders

Previous research has noted a tendency of normal weight SCC to exhibit MOE values lower than those of conventionally vibrated high performance concrete (HPC) of the same compressive strength. Gross et al.[6] (2007) reported that the SCC used in their research exhibited a 22% lower elastic modulus than high strength concrete of the same compressive strength. Similarly, Holschemacher and Klug[8] (2002) reported that the modulus of elasticity of SCC may be up to 20% lower than the modulus of elasticity of normally vibrated concrete having the same compressive strength. These significant differences in elastic modulus have been attributed to the unique mixture composition of SCC. SCC typically contains a higher cement paste volume while having a reduction in the amount of coarse aggregate when compared to conventional concrete mixtures.

Future research in this project may include mixing and testing conventionally vibrated lightweight high strength concrete to compare directly between mixes. However, when measured MOE of LWSCC is compared to the prediction equations, there does not appear to be as much of a pronounced difference as reported by researchers investigating properties of normal weight SCC.

*Future research is to be conducted before final submission, reporting more information on MOE of LWSCC.

PRESTRESS LOSSES

The two DT beams were instrumented to record strain at or near the c.g.s. in the cross sections of the beams. The strains measured were converted to stresses by multiplying the change in strain by the elastic modulus of the prestressing strand (taken to be 28,500 ksi).

$$\Delta f_{ps,measured} = E_{ps}\varepsilon_{cgs,measured} \qquad \text{(Eqn. 1)}$$

ELASTIC SHORTENING LOSSES

Elastic shortening losses occur instantly after transfer of prestress force to the members. The concrete around the strands shortens upon application of prestress. A baseline reading was made prior to transfer. Readings were recorded at three minute intervals during the transfer process, and readings were made after 1) the strands were cut on the ends of the beams and 2) the strands were cut freeing each individual beam. Table 4 shows the measured values of prestress losses after cuts. It should be noted that all predictions are based of an assumed modulus of elasticity of 2732 ksi at transfer, which corresponds to the AASHTO/ACI prediction equation incorporating measured compressive strength prior to transfer and measured unit weight. Future research in this project will incorporate measurement of MOE at transfer to determine the validity of this assumption.

Table 7 shows comparisons between refined predicted elastic prestress loss values and measured values. Relaxation values were added to the measured values since the concrete does not exhibit strain from relaxation of the prestressing steel. A trend was noticed regarding measured losses immediately after strands were cut at the ends of the prestressing bed. Predicted losses were much greater than measured losses at this time. For example, the predicted-to-measured ratio for DT-32 ranges from 6.00 to 6.78. Additionally, DT-59 has predicted-to-measured ratios of 4.37 to 5.19. A similar trend was noted after strands on both ends were cut on DT-59. A possible explanation of these large differences is a large frictional force of the bed acting on the concrete, reducing elastic shortening of the concrete. If friction reduces the ability for the concrete to shorten under transfer, then elastic shortening may not fully occur until the frictional restraint is removed. Cook et al.[5] (2005) reported that they observed a significant increase in camber after the girders in their study were removed from the bed, likely due to a horizontal restraint because of the frictional force present between the bed liner and the girder. They also reported this effect would be more pronounced on longer girders. This trend seems to explain the difference in predicted/measured values for beams DT-32 and DT-59 even after strands from both ends were cut free. A large frictional force could lead to less than expected values in both elastic prestress losses and initial camber.

Table 4: Elastic shortening losses at different times relative to transfer

	Refined Methods	Imd. After Bed End Strands Cut	Predicted/ Measured	After Both End Strands Cut	Predicted/ Measured	4.7 Hours After Transfer	Predicted/ Measured
DT-32	AASHTO-LRFD (2007)	14.49	6.14	14.49	1.38	14.66	1.03
	PCI-DH (2004)	14.17	6.00	14.17	1.35	14.36*	1.01
	PCI-BDM (2003)	14.49	6.14	14.49	1.38	14.70*	1.04
	NILSON (1987)	16.00	6.78	16.00	1.53	16.21*	1.14
	Measured + Relaxation	2.36	1.00	10.49	1.00	14.17	1.00
DT-59	AASHTO-LRFD (2007)	15.51	4.47	15.51	3.89	15.68	1.20
	PCI-DH (2004)	15.18	4.37	15.18	3.80	15.39*	1.18
	PCI-BDM (2003)	15.51	4.47	15.51	3.89	15.73*	1.20
	NILSON (1987)	18.00	5.19	18.00	4.51	18.23*	1.40
	Measured + Relaxation	3.47	1.00	3.99	1.00	13.06	1.00

*Denotes value was adjusted to include 4.7 hours of time-dependent losses based on an estimate not explicitly accounted for in prediction methods

Four refined prestress loss prediction methods were compared to measured results. These include: 1) the AASHTO-LRFD Bridge Design Specification (2007) refined method[3], 2) the PCI Design Handbook (2004) refined method[9], 3) the PCI Bridge Design Manual (2003)[10] (which refers to the current AASHTO-LRFD Specifications at the time of publication, and 4) the Nilson Prestressed Concrete Design (1987) refined method[11]. Each prediction method has at least some difference in prediction. It should be noted, however, that the AASHTO-LRFD (2007) method predicted the same elastic shortening loss as the PCI-BDM (2003) method. This occurred due to the same equations predicting elastic shortening losses. However, differences exist between the two methods when considering time dependent losses. Changes to the AASHTO-LRFD Specifications occurred after Tadros made recommendations in NCHRP Report 496[13] in 2003. Out of all of the refined methods evaluated, the AASHTO-LRFD (2007) refined method is the only one that accounts for time after release. To evaluate losses at the time that the beams were removed by crane and transported to a temporary storage area, time dependent losses were added to the elastic shortening losses. Using the AASHTO-LRFD (2007) method, an estimate was made that approximately 0.75% of the losses over an 83-day period would occur during the first 4.7 hours after transfer. Therefore, 0.734% and 0.749% of the calculated time-dependent prestress losses were added for the beams DT-

32 and DT-59, respectively. This small adjustment added approximately 0.2 ksi to each elastic shortening loss value.

The PCI Design Handbook (2004) refined method provided the estimate most closely matching measured values. After both strands were cut, the predicted-to-measured values were 1.35 and 3.80 for beams DT-32 and DT-59, respectively. Also, at 4.7 hours after release, the estimate was within 1 percent of the measured value of DT-32. The predictions were closest to measured values at 4.7 hours. For example, values of predicted/measured ranged from 1.01 to 1.14 for DT-32 and 1.18 to 1.40 for DT-59. The AASHTO-LRFD (2007), PCI-DH (2004), and PCI-BDM (2003) all provided reasonably similar estimates of elastic shortening losses. The Nilson (1987) method typically overestimated prestress losses by a higher percentage than other standard methods. More variance between methods occurs when considering time-dependent prestress losses.

TOTAL PRESTRESS LOSSES

Total prestress losses include losses due to elastic shortening and time-dependent losses. Figure 8 shows measured prestress losses from transfer to 83 days after transfer. Time-dependent losses include effects of concrete shrinkage, concrete creep, and steel relaxation. All four predictions take these three effects into account and calculate losses separately for each. For comparison purposes, total losses measured and estimated are displayed in Figure 8 at 26 days (time of last measurement on precast plant yard) and at 83 days (shortly after erection and before any topping slabs were poured). Again, relaxation values were added to measured values to compensate for a change undetectable by VWSGs.

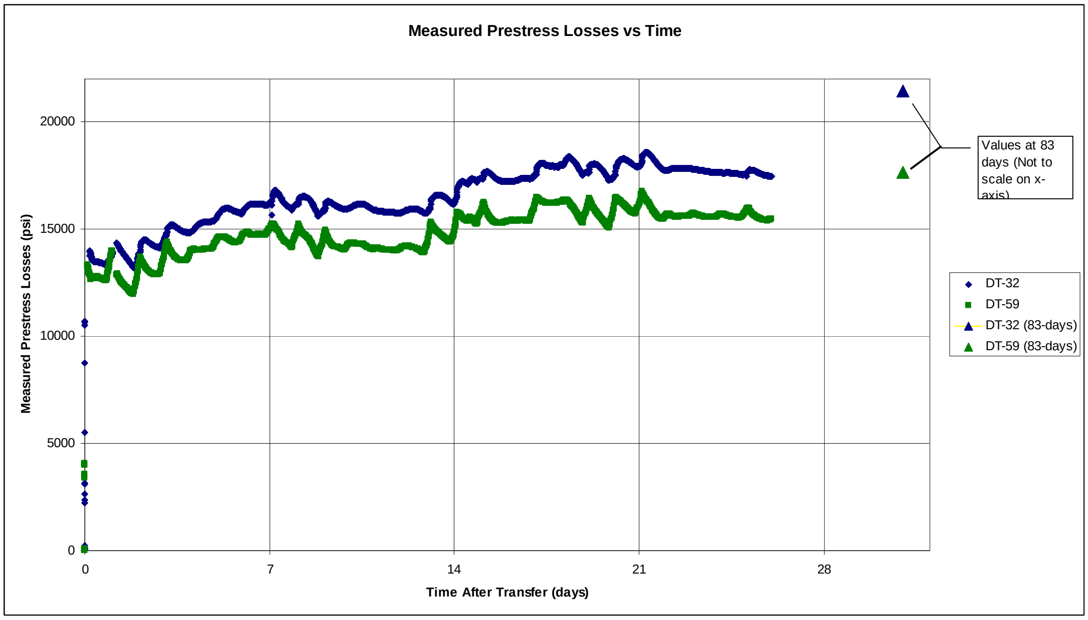

Figure 8: Measured prestress losses versus time (first 26 days + 83 day reading)

Table 5: Total Prestress losses estimated vs. measured values

	Refined Methods	26 Days After Transfer	Predicted/ Measured	83 Days After Transfer	Predicted/ Measured
DT-32	AASHTO-LRFD (2007)	28.25	1.56	37.90	1.73
	PCI-DH (2004)	39.91	2.21	39.91	1.82
	PCI-BDM (2003)	42.66	2.36	42.66	1.94
	NILSON (1987)	44.44	2.46	44.44	2.02
	Measured + Relaxation	18.06	1.00	21.95	1.00
DT-59	AASHTO-LRFD (2007)	28.66	1.79	37.69	2.08
	PCI-DH (2004)	43.31	2.71	43.31	2.39
	PCI-BDM (2003)	44.86	2.81	44.86	2.48
	NILSON (1987)	48.98	3.06	48.98	2.70
	Measured + Relaxation	15.99	1.00	18.12	1.00

For total losses, the AASHTO-LRFD (2007) refined method provides the closest predicted/measured value. This is especially true at 26 days. Since the AASHTO-LRFD method accounts for time, it can more accurately estimate losses that occur at differing times. The predicted/measured values of the AASHTO-LRFD method are 1.56 and 1.79 at 26 days for beams DT-32 and DT-59, respectively. For these two beams, the predicted values overestimated measured values in every case. The greater difference between predicted values and measured values of total losses at 83 days compared to those shortly after release indicates that the time-dependent losses are the primary reason for a discrepancy. This discrepancy could be caused by a number of things due to the complex nature of prestress losses. One important item to consider for LWSCC that may not affect normal weight SCC or other conventional mixes is the internal curing characteristics provided by the lightweight aggregates within LWSCC.

When lightweight aggregates contain high internal moisture contents prior to mixing (due to pre-wetting of the aggregate), internal curing may occur within the concrete member. Since the lightweight aggregates used in this mix are very porous, there is a great amount of volume that may be occupied by water. Moisture is slowly released from the pores of the lightweight aggregate to the cementitous fraction of the concrete matrix, allowing for continued hydration over time. Shrinkage of concrete containing lightweight aggregate may be slightly greater than that of concrete containing normal weight aggregate; however, due to high pre-wet moisture contents of lightweight aggregate, lightweight concrete may have shrinkage that plateaus at a later time[7]. Internal curing may delay time-dependent losses and lead to differences between predicted and measured prestress losses.

CAMBER

Camber was measured on beams DT-32 and DT-59 at the same time the above reported prestress losses were recorded. A baseline reading was made prior to removal of the depression frame and prior to transfer. All subsequent calculations subtracted this initial baseline reading to get camber values. A 50 scale on an engineer's scale was used to measure camber. On a 50 scale, markings are present every 0.02". Consequently, the deliverable accuracy of each measurement is expected to be within 0.04". Table 6 shows the predicted and measured initial camber values. Initial camber has two components. There is an upward component due to the eccentric loading of the prestressing steel acting on the member. A downward component caused by the member's self-weight partially offsets the upward component. Typically, there will be a net upward camber.
The upward component for a single point depressed beam is calculated as follows:

$$\Delta \uparrow = \frac{P_0 e_e l^2}{8E_{ci}I} + \frac{P_0 e' l^2}{12E_{ci}I} \text{; where:}^{9} \qquad \text{(Eqn. 2)}$$

P_0 is the prestress force at transfer (kip),
e_e is the eccentricity at the end of the member (in),
e' is the difference in eccentricity between the end and at midspan,
l is the length of the member (in),
E_{ci} is the modulus of elasticity of the concrete at transfer (ksi),
I is the moment of inertia of the section (in^4) **Reference PCI-DH

The downward component of camber deflection is calculated as follows:

$$\Delta \downarrow = \frac{5wl^4}{384E_{ci}I} \text{; where:}^{9} \qquad \text{(Eqn. 3)}$$

w is the unfactored load per unit length of beam due to self weight (lb/ft).[9]

Table 6: Comparison of initial camber prediction to measured values

	Initial Camber	Imd. After Bed End Strands Cut	After Both End Strands Cut	4.7 Hours After Transfer
DT-32	Predicted Initial Camber	0.47	0.47	0.47
	Measured Initial Camber	-0.01	0.25	0.60
	Predicted/Measured	-47.00	1.88	0.78
DT-59	Predicted Initial Camber	1.31	1.31	1.31
	Measured Initial Camber	0.00	-0.01	1.03
	Predicted/Measured	∞	-131.00	1.27

A similar trend is noted in Table 6 with initial camber as was noted in Table 4 for elastic prestress losses. A likely explanation is the horizontal restraint due to friction between the bed and concrete beam, disallowing elastic shortening and full prestress transfer to the beam. The two negative values of -0.01" for the two beams are actually not likely negative changes in camber, but rather the -0.01" shows no change in camber and can be explained by the accuracy of the measurements, estimated at 0.04”. The predictions at 4.7 hours after transfer represent the closest matches of predicted-to-measured values. The prediction somewhat underestimates the measured camber for DT-32 while overestimating camber for DT-59.

Camber growth was also evaluated in this program. Figure 9 shows measured camber versus time over the 83 day period evaluated in this project. The 83rd day after transfer corresponds to the time shortly after erection and prior to the topping slabs being poured.

Both beams exhibited increasing camber growth (at a decreasing rate) until approximately 21 days. Little camber growth was observed between 21 days and 83 days. The exact amount of camber growth during this time is unclear due to changes in support condition and possible effects from thermal gradients. It should also be noted that transporting beams may affect camber. Camber was measured approximately 1 day after transfer, shortly before and shortly after movement. There was a noticeable decrease in camber in both beams after movement. This is likely due to a change in support. Cranes lift the beams with supports near the ends of the beams in line with the stems of the double-tees. The downward component due to member self-weight is more pronounced, and therefore the camber decreases slightly.

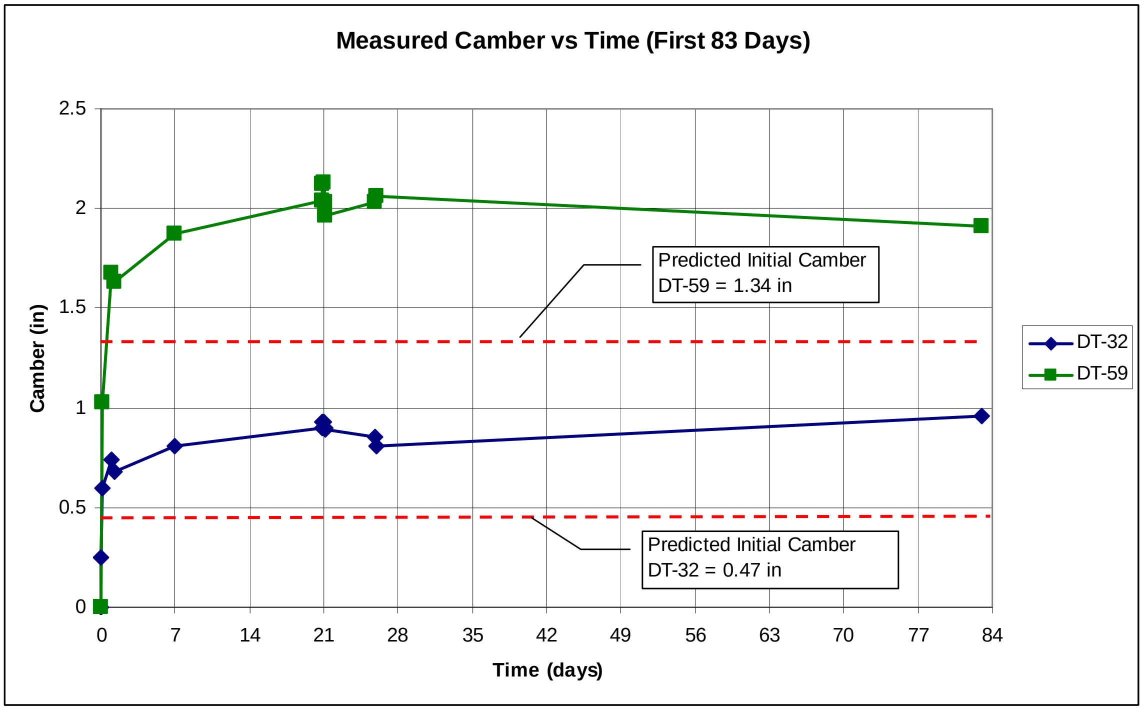

Figure 9: Measured camber versus time for the first 83 days after transfer

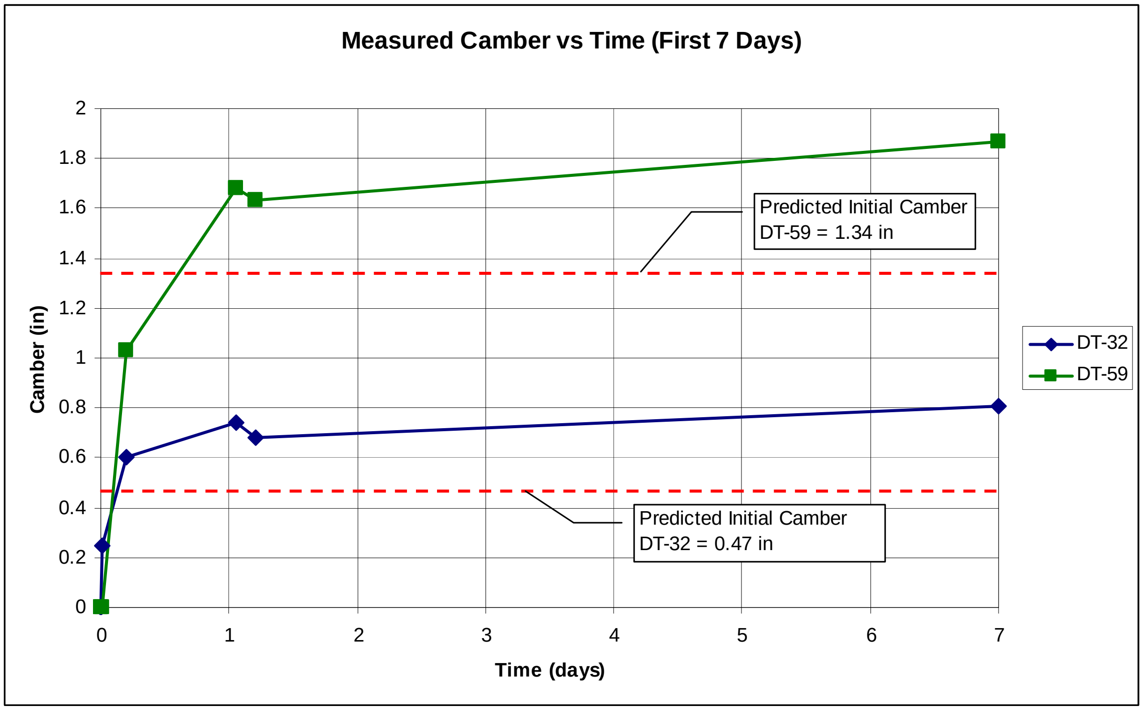

Figure 10: Measured camber versus time for the first 7 days after transfer

An attempt was made to empirically correct measured camber for the presence of thermal gradients. At 21 days, camber measurements were taken at 8:00 a.m., 10:00 a.m., 12:00 p.m., 2:00 p.m., and 4:00 p.m. However, the weather was partly cloudy and cool, with a cool wind blowing throughout the day. There was little solar energy and warming during the day to produce measurably noticeable differences in camber. Therefore, further research may include instrumenting similar girders with several thermocouples along the vertical profile of the cross section of the member and measuring changes in camber with changes in internal temperature. This then could be correlated to the changes between the two thermistors in each stem where the embedded strain gauges were located in beams DT-32 and DT-59.

Table 7 again shows the effects from restraints acting from the bed to the beam, reducing initial camber before transportation from the bed. All of the camber measurements were calculated using the above equations 2 and 3 using different effective prestress forces based on initial strand stress minus losses predicted by different prestress loss methods. Concerning initial camber, there was very little difference between predicted initial camber using predicted prestress loss values compared to using measured prestress loss values. However, the measured camber exhibits approximately 30% higher camber than predicted for beam DT-32, while DT-59 exhibits approximately 22% lower camber than predicted.

Table 7: Camber estimates based on various elastic shortening prestress loss predictions and actual measured losses (All camber values are in inches.)

	Prestress Loss Est.	Imd. After Bed End Strands Cut	Predicted/ Measured	After Both End Strands Cut	Predicted/ Measured	4.7 Hours After Transfer	Predicted/ Measured
DT-32	AASHTO-LRFD (2007)	0.47	-47.00	0.47	1.88	0.47	0.78
	PCI-DH (2004)	0.47	-47.00	0.47	1.88	0.47	0.78
	PCI-BDM (2003)	0.47	-47.00	0.47	1.88	0.47	0.78
	NILSON (1987)	0.46	-46.00	0.46	1.84	0.46	0.77
	Based on Measured	0.47	-47.00	0.47	1.88	0.47	0.78
	Actual Measured Camber	-0.01	1.00	0.25	1.00	0.6	1.00
DT-59	AASHTO-LRFD (2007)	1.31	∞	1.31	-131.00	1.31	1.27
	PCI-DH (2004)	1.31	∞	1.31	-131.00	1.31	1.27
	PCI-BDM (2003)	1.31	∞	1.31	-131.00	1.31	1.27
	NILSON (1987)	1.27	∞	1.27	-127.00	1.27	1.23
	Based on Measured	1.34	∞	1.34	-134.00	1.34	1.30
	Actual Measured Camber	0.00	∞	-0.01	1.00	1.03	1.00

Table 8: Estimated camber at erection (83-days after transfer) using a multiplier method

	Multiplier Method based on Prestress Loss Est.	At Erection 83-days	Predicted/ Measured
DT-32	AASHTO-LRFD (2007)	0.84	0.88
	PCI-DH (2004)	0.84	0.88
	PCI-BDM (2003)	0.84	0.88
	NILSON (1987)	0.83	0.86
	Based on Measured	0.84	0.88
	Actual Measured Camber	0.96	1.00
DT-59	AASHTO-LRFD (2007)	2.29	1.18
	PCI-DH (2004)	2.30	1.19
	PCI-BDM (2003)	2.29	1.18
	NILSON (1987)	2.23	1.15
	Based on Measured	2.37	1.22
	Actual Measured Camber	1.94	1.00

Table 8 shows estimated camber at erection using the four previously discussed prestress loss estimation methods. All of the values predict the camber within 20% of the actual measured value. The predicted/measured values for these estimates vary less from 1.00 than did the initial camber estimations. The multiplier method involved multiplying a factor of 1.80 to the calculated upward initial camber component and 1.85 to the downward initial camber component.

Future research will evaluate the improved multiplier method as well as possible time step analysis methods.

TRANSFER AND DEVELOPMENT LENGTH

Findings regarding transfer and development length will be included in a later draft of this paper.

CONCLUSIONS

The goal of this research program was to provide information on the behavior and performance of LWSCC. Conclusions of this research program include:

- The ACI/AASHTO methods for predicting modulus of elasticity of concrete provide reasonable estimates of measured values at 7 days, 28 days and 90 days.
- Horizontal restraints due to friction play a role in delaying elastic shortening losses and initial camber. This trend is especially noticed in longer members.
- All elastic prestress loss methods overestimated prestress losses; however, the methods provided reasonable estimates when compared to the measured prestress losses at 4.7 hours after prestress transfer.
- The AASHTO-LRFD (2007) Bridge Design Specification method provided the best total prestress loss prediction at both 26 and 83 days.
- Camber growth was monitored and most estimates using the multiplier method were within 20% of the measured values at erection at 83 days.
- Further research is needed to better understand the behavior and performance of LWSCC

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