PRESTRESS LOSSES OF TWO HIGH PERFORMANCE CONCRETE BRIDGES IN VIRGINIA

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ABSTRACT

An experimental program was planned and executed with the general objectives of quantifying prestress losses for high strength normal-weight and lightweight concretes in Virginia and comparing these losses to those predicted using various prestress loss models, including ACI-209-90, CEB-FIP-90, the PCI time-step method, and others. To accomplish this, several girders from two bridges in Virginia were instrumented with vibrating wire strain gages at the level of the centroid of the prestressing force at midspan. An 8,000 psi lightweight HPC was used in the Chickahominy River Bridge near Richmond, Virginia, which utilized AASHTO Type IV girders spanning 82 ft and spaced 10 ft apart. An 8,000 psi normal-weight HPC was used to cast AASHTO Type V girders, spanning 86 feet and spaced 8.5 ft apart, for the Pinner's Point Bridge in Portsmouth, Virginia. Both sets of girders were then continually monitored, both in the casting yard and after erection, to determine the long-term prestress losses.

Keywords: High Performance Concrete (HPC), Prestress Losses, Lightweight Concrete (LWC), High Strength Concrete, Creep, Shrinkage

INTRODUCTION

High performance concretes (HPC) have become common in precast prestressed bridge girders in recent years. These concretes allow increased structural and economic efficiencies in highway bridge design over their normal counterparts due to their increased strength and durability. The design of HPC precast prestressed girders is often controlled by service load stresses in the bottom flange, where cracking is the major concern. Prestress losses, and an accurate prediction thereof, is an important consideration in girder design and structural efficiency at service loads. A significant over-prediction of prestress losses, while not detrimental to the girder's ultimate strength, will result in a significant over-design at service loads.

An experimental program was planned and executed with the general objectives of quantifying prestress losses for high performance normal-weight and lightweight concretes in Virginia and comparing these losses to those predicted using various prestress loss models, including ACI-209R-92[1], CEB-FIP-90[2], the PCI time-step method[3], and others. To accomplish this, several girders from two bridges in Virginia were instrumented with vibrating wire strain gages at the level of the centroid of the prestressing force at midspan. An 8,000 psi lightweight HPC was used in the Chickahominy River Bridge near Richmond, Virginia, which utilized AASHTO Type IV girders spanning 82 ft and spaced 10 ft apart. An 8,000 psi and a 10,000 psi normal-weight HPC were used to cast AASHTO Type V girders, spanning 86 feet and spaced 8.5 ft apart, for the Pinner's Point Bridge in Portsmouth, Virginia. Both sets of girders were then continually monitored, both in the casting yard and after erection, to determine the long-term prestress losses.

MOTIVATIONS

Effective determination of long-term prestress losses is an integral part of the design of prestressed concrete bridges. Elimination of cracking at service loads controls the design of many prestressed girders, and prestress losses directly influence the service load stresses. An over-prediction in prestress losses results in an overly conservative design for service load stresses, while an under-prediction in prestress losses, depending on the severity of the under-prediction, could result in significant cracking at service loads. An over-prediction of prestress losses can also cause further design inefficiencies by limiting the span length of a girder, and by requiring a larger initial prestressing force to resist the applied loads, which, in turn, produces excessive camber.

Initial research studies, most notably that of Tadros et. al.[4], have shown that HPC tends to exhibit less creep and shrinkage than does conventional concrete. This reduced creep and shrinkage tends to reduce the total long-term prestress losses below that exhibited by conventional concrete. The current creep and shrinkage models used by the AASHTO Specifications were developed for conventional concrete; therefore, they should over-predict the creep and shrinkage, and in turn, the long-term prestress losses of HPC. This study aims to determine if this is true of the HPC mixes used in Virginia and to provide recommendations for the determination of prestress losses for HPC girders in Virginia.

INSTRUMENTED BRIDGES

Two bridges utilizing HPC were instrumented with vibrating wire gages to monitor the strains at the centroid of the prestressing force over time and to determine the long-term prestress losses associated with HPC. The Chickahominy River Bridge was constructed utilizing high performance lightweight concrete (HPLWC), and the Pinner’s Point Bridge was constructed utilizing conventional HPC. The details of each bridge are presented in the following sections, and the properties of the instrumented girders in each of the bridges are summarized in Table 1.

Table 1 – Summary of Research Bridges

Bridge	Girder ID	Interior or Exterior	Girder Type	Specified Strength Rel. / 28-day psi	Span	Girder Spacing
Chickahominy River (LWC)	1	Exterior	AASHTO Type IV	5,600 / 8,000	82' – 10"	10' - 0"
	2	Interior			81' – 10 ¼"	
	3					
Pinner’s Point	F	Interior	AASHTO Type V	6,400 / 8,000	85' – 4 ¼"	8' – 7 ½"
	T				86' – 1 ¼"	7' – 11"
	U	Exterior			86' – 8 ¾"	
	G	Interior		6,400 / 10,000	86' – 0"	8' – 7 ½"
	H				86' – 7 ¾"	
	J	Exterior			87' – 3 ½"	

CHICKAHOMINY RIVER BRIDGE

The Chickahominy River Bridge was constructed in the spring of 2001, near Richmond, VA, utilizing AASHTO Type IV girders, and is the first bridge in Virginia to utilize HPLWC precast girders. The specified concrete strength of the girders was 4,500 psi at release and 8,000 psi at 28-days with a unit weight of 120 pcf. The bridge girders attained an average strength at release of 4,700 psi and a 28-day strength of 8,100 psi. The bridge contains five girders in each of three spans spaced 10 ft apart. The outer spans are approximately 83 ft, while the center span is approximately 82 ft. Three of the Chickahominy River Bridge girders were instrumented to monitor long-term strains according to the gage plan shown in Figure 1. The instrumented girders included an exterior girder in the middle span and one interior girder in each of the outer spans. Each of these girders was instrumented with three vibrating wire gages (Figure 2) at midspan at the centroid of the prestressing force and strains were logged every two hours. Each vibrating wire gage also contains a thermistor allowing the raw strain measurements to be corrected for differences in the thermal coefficients of the vibrating wire gage and the concrete.

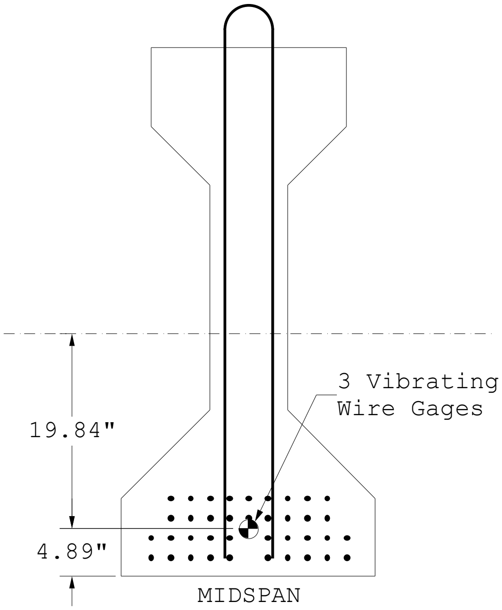

Figure 1 - Instrumentation of Chickahominy River Bridge Girders

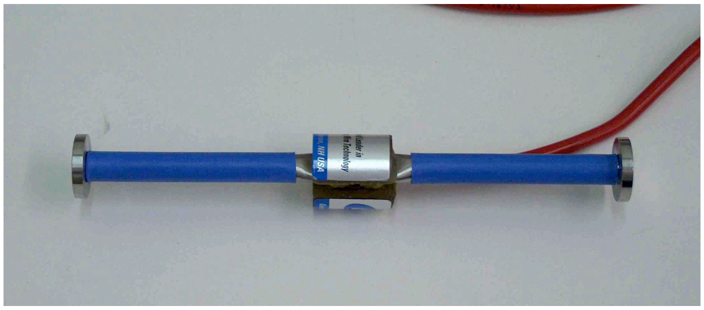

Figure 2 – Vibrating Wire Gage

Prior to the construction of the Chickahominy River Bridge Adil Nassar[5] carried out research at Virginia Tech relating to the design and implementation of HPLWC. This research focused on the issues of transfer and development length and flexural strength. However, three test girders, identical to those in the bridge, were constructed and instrumented to monitor prestress losses. The test girders achieved an average release strength was 4,800 psi, and an average 28-day strength was 7,800 psi. Although the 28-day strength was slightly below the design value, the average strength at 180 days was 9,000 psi. These girders were left in the casting yard and monitored for prestress losses in the absence of any applied dead loads.

PINNER'S POINT BRIDGE

Construction of the Pinner's Point Bridge began in the spring of 2003. Six of the bridge's AASHTO Type V HPC girders were instrumented with vibrating wire gages and four girders were instrumented with thermocouples in the summer of 2002 as shown in Figure 3. The specified release strength for all six girders was 6,400 psi, and the specified 28-day strength for three of these girders was 8,000 psi, while for the other three, the 28-day strength was 10,000 psi. The average release strength for the 8,000 psi girders was 6,600 psi and the average 28-day strength for these girders was 8,600 psi. For the 10,000 psi girders, the average release strength was 7,500 psi, and the average 28-day strength was 10,800 psi. The six girders are contained in the first two spans of the bridge and are spaced approximately 8.5 ft apart. Due to the unique geometry of the bridge, however, each girder is a unique length, ranging from approximately 85 ft to approximately 87 ft.

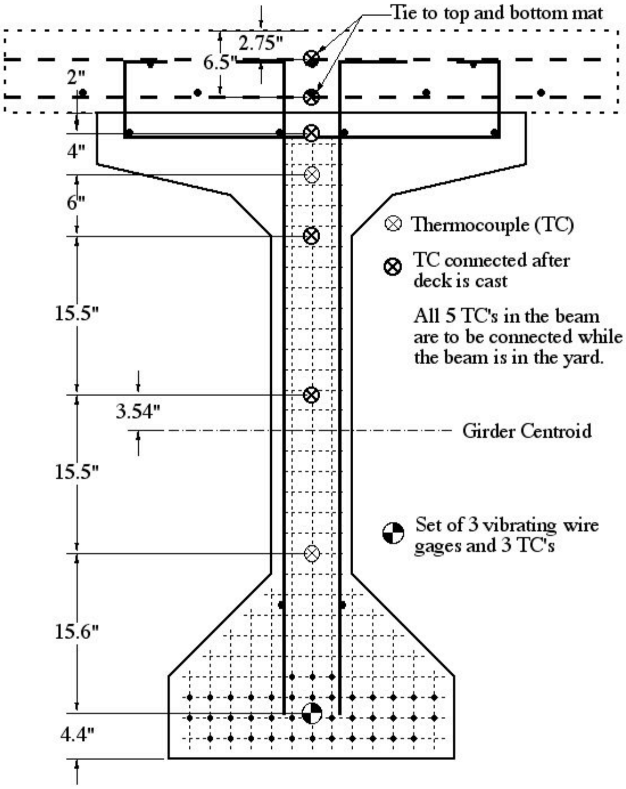

Figure 3 - Instrumentation for Pinner's Point

The three 8,000 psi girders include an interior girder in the first span (Girder F), and interior girder in the second span (Girder T), and an exterior girder in the second span (Girder U). The 10,000 psi girders include two interior girders in the first span (Girders G and H) and an exterior girder in the first span (Girder J). Each of these girders was instrumented with three vibrating wire gages (Figure 3) at midspan at the centroid of the prestressing force and strains were logged every fifteen minutes for the first several days, and then every two hours thereafter. Each vibrating wire gage also contains a thermistor allowing the raw strain measurements to be corrected for differences in the thermal coefficients of the vibrating wire gage and the concrete. Furthermore, four girders were instrumented with thermocouples to provide a better measure of the temperature changes and gradients in the girders, and this data was used in conjunction with thermistors in the vibrating wire gages to adjust the measured strains for temperature changes in the girders.

RESULTS AND DISCUSSION

The measured strains from the Chickahominy River Bridge and the Pinner's Point Bridge were compared to the strains determined using several creep and shrinkage models, including ACI-209R-92[1], CEB-FIP-90[2], the PCI time step method[3], and that of Tadros, et. al[4]. Furthermore, the prestress losses for each girder were determined from the measured strains, and were compared to the losses determined using the recommendations of the AASHTO Standard[6] and LRFD[7] Specifications, and the approximate method of Tadros et. al.[4]

CHICKAHOMINY RIVER BRIDGE

Prior to the construction of the Chickahominy River Bridge several test girders were cast and monitored in the precasting yard to estimate the prestress losses associated with the HPLWC used in the bridge. The strain at the centroid of the prestressing force in these girders has since been monitored for almost two years. The recorded strains and the strains determined using several models for creep and shrinkage are shown in Figure 4. For each of the creep and shrinkage models, strains were determined in a time step fashion, with a time step of one day, and include elastic shortening, steel relaxation, creep, shrinkage, and any gain in strain due to the prestress losses for each time step. The same elastic shortening and steel relaxation losses were used for each model, and the various strains are due only to the application of the various creep and shrinkage models.

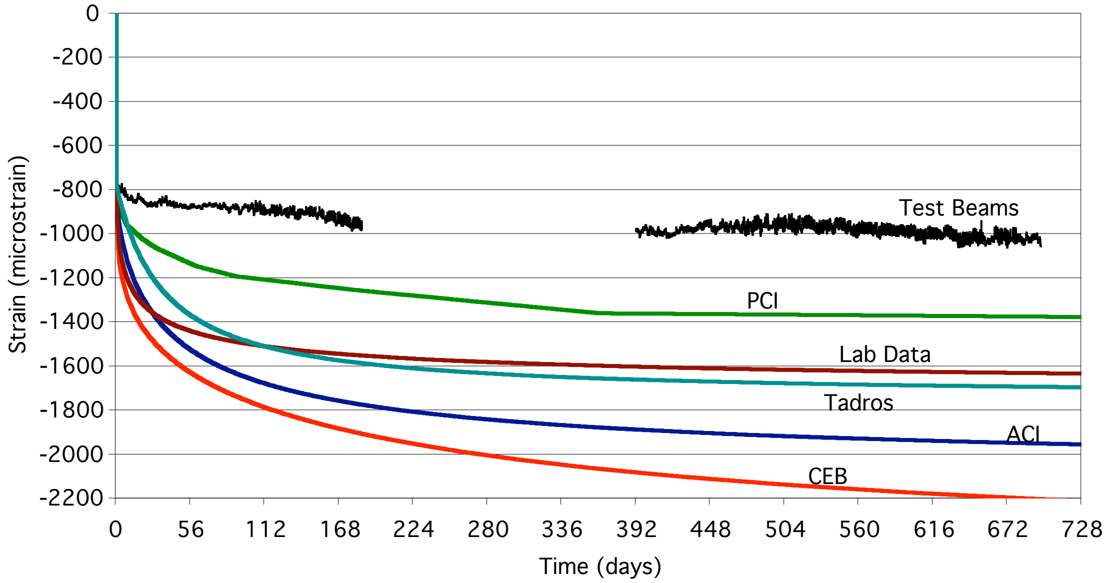

Figure 4 – Comparison of Test Beams to Models

In addition to the creep and shrinkage models shown on the plot, a laboratory investigation of the creep and shrinkage properties of the HPLWC was performed at Virginia Tech[8]. The data from this study was curve-fit to develop a model for the laboratory behavior, and the ACI-209 correction factors for non-standard environmental conditions were applied to determine the prestress losses in the bridge predicted by the laboratory data. The curve resulting from this analysis is also shown in Figure 4.

Each creep and shrinkage model investigated over-predicted the creep and shrinkage strains observed in the test girders. The PCI time step method produced the closest results, over-predicting the total strain by 40% at two years. The CEB-FIP-90 creep and shrinkage model was the worst predictor, over-predicting the strains by 120% at approximately two years. These results were expected given the previous research indicating that the current prestress loss models over-predict prestress losses associated with HPC; however, the magnitude of the over-predictions was larger than expected. Surprisingly, however, the laboratory data, adjusted for the different environmental conditions at the job site, also significantly over-predicted the small time-dependent strains seen in the test girders. The small change in strain over time of the test girders was also seen in the Chickahominy River Bridge girders as will be discussed later. It is planned to verify these measurements though destructive testing of the test girders, sometime in the future.

When compared to the creep and shrinkage measurement taken in the laboratory, the Tadros method becomes the best predictor at two years, differing from the measured data by only 4%. The PCI time step method is the only method that under-predicts the laboratory measurements, in this case, by 16%, and CEB-FIP-90 is again the worst predictor, over-predicting by 35%.

In addition to the test girders, three girders from the Chickahominy River Bridge were instrumented and have been monitored for approximately a year and a half. The girders were monitored at the casting yard for approximate two months, at which time they were transported to the bridge site. Due to the inability to access the bridge site, monitoring was suspended for approximately two months until after the girder had been set, and the deck had been cast. The recorded strains are shown in Figure 5, along with strains determined from

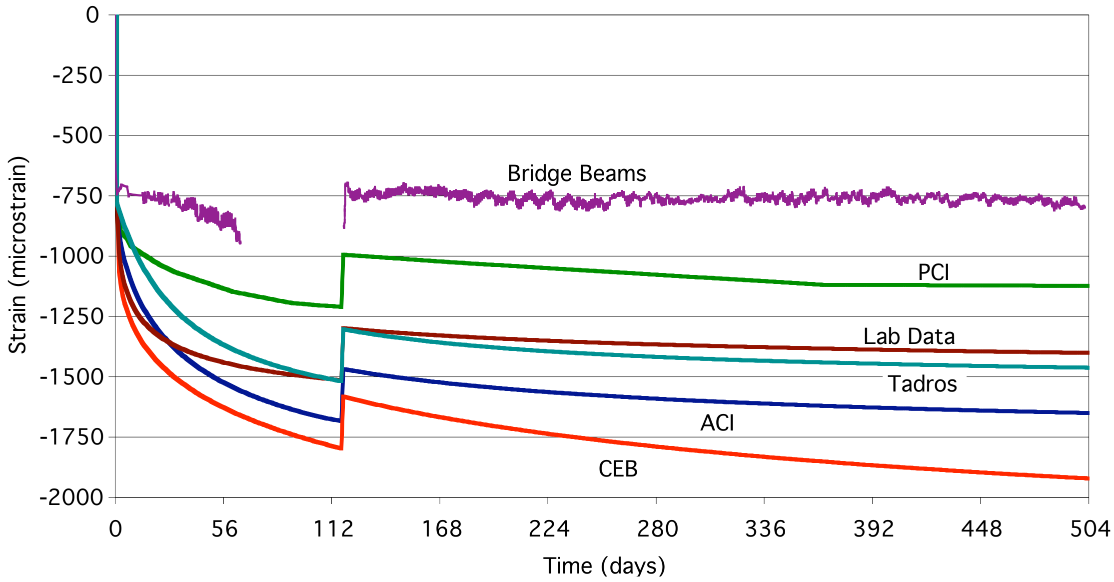

Figure 5 – Comparison of Chickahominy River Bridge Beams to Models

several creep and shrinkage models. Again each of the creep and shrinkage models over-predict the total strain with the PCI time step method again the best predictor, over-predicting by 41% at 500 days, and CEB-FIP-90 the worst predictor, over-predicting by 140% at 500 days. The total strain based on the laboratory data also again over-predicts the strains measured in the girders, in this case by 76%.

As with the test girders, when compared to the laboratory creep and shrinkage data, Tadros is again the best predictor, over-predicting the total strain by 4%. PCI again under-predicts the laboratory data, in this case by 20%, and CEB-FIP-90 is again the worst predictor, over-predicting the laboratory data by 37%.

Prestress losses for the Chickahominy River Bridge were also determined from the methods described in the AASHTO Standard[6] and LRFD[7] Specifications, and the approximate method described by Tadros, et. al.[4] The losses determined for various components of prestress loss are shown in Table 2 along with the total losses determined from the recorded bridge strains. For the AASHTO LRFD lump sum and Tadros approximate methods, the long-term losses are not determined individually, hence only one number is given for creep, shrinkage, and additional steel relaxation losses for these methods. Finally, Table 2 shows the strain in the concrete at the centroid of the prestressing strand due to the total losses.

Table 2 – Summary of Prestress Losses for Chickahominy River Bridge

Method	Initial Losses		Long-Term Losses			Total	Strain at End of Service
	Steel Relaxation	Elastic Shortening	Shrinkage	Creep	Steel Relaxation		
	ksi	ksi	ksi	ksi	ksi	ksi	□□
AASHTO Standard Spec.	2.1	22.8	5.8	25.1	3.2	59.0	-1,884
AASHTO LRFD Spec. General	2.1	22.8	5.8	25.1	4.7	60.5	-1,884
AASHTO LRDF Spec. Lump Sum	2.1	22.8	36.5			61.4	-1,916*
Tadros Approximate	2.1	22.8	21.8			46.7	-1,481#
Chickahominy River Bridge						27.8+	-800

* Additional steel relaxation losses of 4.7 ksi assumed, from AASHTO LRFD general

\# Additional steel relaxation losses of 2.4 ksi assumed, from reference 4

\+ Includes an estimate of 5 ksi for steel relaxation losses.

Steel relaxation losses were not included in the determination of the strain at end of service since these losses occur in the tendon at constant strain. Also, each of the methods for estimating prestress losses also considers the effect of the deck-weight and superimposed dead load on the prestress losses; so the strain determined from the estimated losses can be directly compared with the strains recorded from the bridge girders. Finally, the strains recorded from the Chickahominy River Bridge should be adjusted to the end of service life for the bridge, however, this adjustment has not been made since the observed strains remain mostly flat after the deck is cast.

When this comparison is made, the Tadros approximate method is best predictor of the measured prestress losses, over-predicting the total strain, and hence the losses by 59%. The AASHTO LRFD lump sum method is the worst predictor of total strain, and hence losses, over-predicting by 113%

PINNER'S POINT BRIDGE

A similar study to that performed on girders from the Chickahominy River Bridge was performed for girders from the Pinner's Point Bridge. Six girders of the Pinner's Point Bridge were instrumented and have been monitored for 14 weeks resulting in the strains shown in Figure 6. Also shown in Figure 6 are the strains calculated from applying several creep and shrinkage models to the six girders from the Pinner's Point Bridge. As was the case with the Chickahominy River Bridge, the Pinner's Point girders exhibit less total strain, and therefore, less prestress loss than is predicted by any the creep and shrinkage models investigated. For the first five weeks, the Tadros method is the best predictor, matching the data almost exactly during the first two weeks and beginning to deviate from the measured data after the first two weeks. After 14 weeks, the Tadros method over-predicts the total strain by 44%. After the first five weeks the PCI method becomes the best predictor, over-predicting the measured strain by 38% after 14 weeks. The CEB-FIP-90 model is again the worst predictor for total strain, over-predicting the total strain by 91% after 14 weeks.

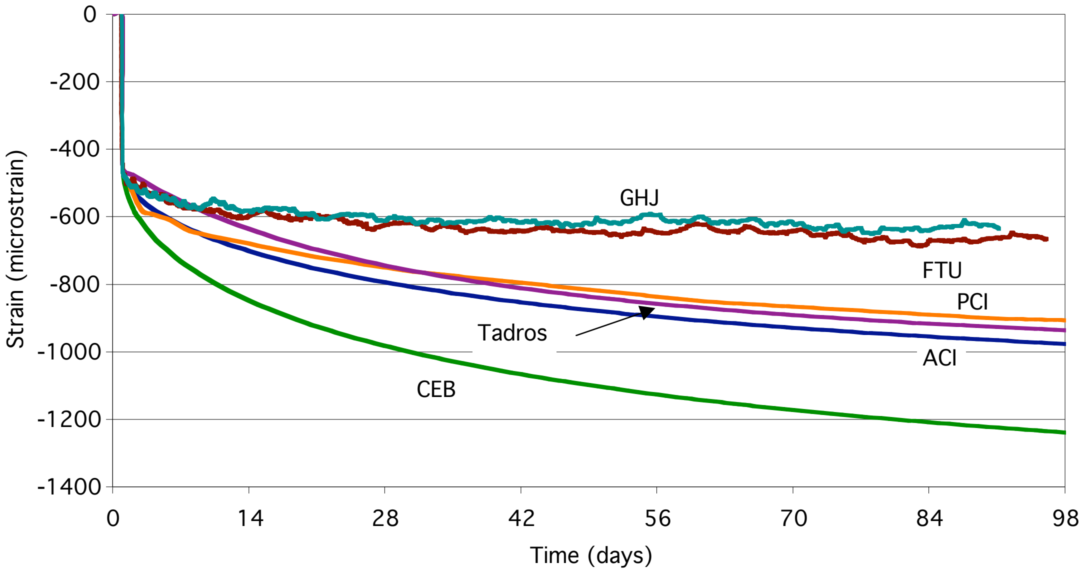

Figure 6 – Comparison of Pinner's Point Bridge Beams to Model

Prestress losses for the six girders were again determined for the methods described in the AASHTO Standard[6] and LRFD[7] Specifications, and those described by Tadros, et. al.[4] The calculated losses were similar for all six girders as the change in the concrete strength from 8,000 psi to 10,000 psi for three of the girders had little effect. Therefore, the average losses determined for all six girders are presented in Table 3. The change in strain in the prestressing steel due to the total losses is also given in Table 3. As was the case with the previous calculations for the Chickahominy River Bridge, these loss calculations include an allowance for the reduction in creep due to the application of dead load; therefore, it is not possible to compare these strains and losses with the current data from the Pinner's Point Bridge, as the data only includes the time the girders were stored in the casting yard. Construction on the Pinner's Point Bridge began in the spring of 2003 when the six instrumented were shipped to the job site. Once the deck forms are in-place, and access to the job site is established, monitoring of the girders will continue.

Table 3 – Summary of Prestress Losses for Pinner's Point Bridge

Method	Initial Losses		Long-Term Losses			Total	Strain at End of Service
	Initial Steel Relaxation	Elastic Shortening	Shrinkage	Creep	Additional Steel Relaxation		
	ksi	ksi	ksi	ksi	ksi	ksi	□□
AASHTO Standard Spec.	1.7	13.0	5.8	30.3	3.1	53.9	-1,723
AASHTO LRFD Spec. General	1.7	13.0	5.8	30.3	7.6	58.4	-1,723
AASHTO LRDF Spec. Lump Sum	1.7	13.0	35.3			50.0	-1,428*
Tadros Approximate	1.7	13.0	18.0			32.7	-1,004[#]
Pinner's Point						23.5[+]	-650

* Additional steel relaxation losses of 7.6 ksi assumed, from AASHTO LRFD general

[#] Additional steel relaxation losses of 2.4 ksi assumed, from reference 4

\+ Includes 5 ksi for steel relaxation. Losses determined from strains at 95 days (deck not yet cast)

FUTURE RESEARCH

The study of prestress losses in HPC is an ongoing project in Virginia. It is planned to continue to monitor the Chickahominy River Bridge for at least another year. Furthermore, destructive testing of the test girders from the Chickahominy River Bridge is in the planning stages. Destructive testing of these girders will be used to determine the actual stress level in the prestressing strands and to verify the small changes in strain over time recorded in both the test girders and the Chickahominy River Bridge girders. The destructive testing will also provide a definitive determination of the stress level in the prestressing strands for comparison with the various prestress loss models.

Once access to the Pinner's Point jobsite can be established, the monitoring of the six girders will resume. It is planned to monitor these girders for at least another year to determine the long-term prestress losses associated with this bridge. Also, a laboratory creep and shrinkage study of the HPC mix used in the Pinner's Point Bridge was recently completed at Virginia Tech[9]. The results from this study will be used to model the long-term strains of the Pinner's Point Bridge as was done with the laboratory data from the Chickahominy River Bridge. The long-term strains from the laboratory data will also be compared to other models investigated to determine which model best predicts the behavior of the HPC used in the Pinner's Point Bridge.

Finally, a third bridge utilizing PCBT-45 girders in Chesapeake, Virginia will be added to the study in the summer of 2003. A laboratory study of the creep and shrinkage properties of the HPC used in this bridge will also be conducted at Virginia Tech using concrete specimens cast and cured alongside the bridge girders. The girders from this bridge will then be monitored to determine the long-term prestress losses.

CONCLUSIONS

The Chickahominy River Bridge utilized a lightweight HPC with a specified release strength of 4,500 psi and a specified 28-day strength of 8,000 psi. After monitoring three test girders for two years, for which no additional dead load was added, it was determined that the current prestress loss and creep and shrinkage models over-predict the total strain and losses in the girders by as much as 120% (CEB-FIP-90). The PCI time step method was determined to be the best predictor, over-predicting the total strain by 40% after two years.

Three girders in the Chickahominy River Bridge were also instrumented and have been monitored for a year and a half. As with the test girders, each of the current models over-predicts the total strain, and therefore, the prestress losses in the girders. PCI is again the best predictor, over-predicting the strain by 41%, and CEB-FIP-90 is again the worst predictor, over predicting the total strain by 140%.

The prestress loss equations presented in the AASHTO Specifications and those presented by Tadros, et. al.[4] were also compared to the total strain recorded in the bridge. The Tadros method was the best predictor, over-predicting the strain by 59%, and the AASHTO LRFD lump sum method was the worst predictor over-predicting the strain by 113%.

The creep and shrinkage characteristics of the HPLWC were investigated in the laboratory and used to model the strain in the bridge beams. The laboratory data, adjusted for the environmental condition of the bridge site using the factors from ACI-209, over-predicted the recorded strains by 40% for the test girders and 76% for the bridge girders. The Tadros creep and shrinkage model was the best match for the laboratory data, over-predicting the laboratory data by only 4% when adjusted for the bridge conditions.

Six girders in the Pinner's Point Bridge were instrumented to determine the loss of prestress. The six girders had a specified release strength of 6,400 psi, and three of the girders had a specified 28-day strength of 8,000 psi, while the other three had a specified release strength of 10,000 psi. After 14 weeks, the PCI time-step method was the best predictor of the total strain, but this method still over-predicted the total strain by 38%. The CEB-FIP-90 model was again the worst predictor, over-predicting the total strain by 91% after 14 weeks.

Further study of the Pinner's Point Bridge will continue once access to the construction site is established. The bridge will then be monitored for at least a year after the deck is cast, and the data will be compared with the current prestress loss models. The laboratory creep and shrinkage data from the HPC used in the Pinner's Point Bridge will also be used to develop a model for the total strain in the bridge girders, and will be compared to the existing models.

Finally, A third bridge utilizing a 9,000 psi HPC and PCBT-45 girders will be added to the study in the summer of 2003.

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