Prestress Losses In High Performance Concrete Beams- Actual Versus Predicted

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ABSTRACT

Accurate prediction of the prestress losses is a very important step in the design of a highly stressed high performance concrete (HPC) girder, and can affect the service behavior of the girder such as deflections, camber, and cracking. Current methods for calculating prestress losses according to the American Association for Highway and Transportation Officials (AASHTO) and the Prestressed Concrete Institute (PCI) were developed for conventional concrete. Further research is needed to determine if the current empirical equations provide an accurate estimate of prestress losses for a HPC girder. Actual prestress losses in HPC girders need to be measured and compared to predicted losses using these equations.

The higher the prestressing force in the girder, the larger the concrete compressive strength needed at release of the prestressing strands. To help achieve the higher release strength, the precast plants have been using longer curing times. Many precast plants are using steam curing to increase the curing rate. A better understanding of the effects of this heating on HPC is needed.

An optical fiber monitoring system was designed and built into a 3 span high performance concrete highway bridge. The Rio Puerco Bridge located 15 miles west of Albuquerque is the first bridge to be built using HPC in New Mexico. The bridge has 3 spans with a length of 29 to 30 m. It is designed to be simply supported for dead load and continuous for live load. HPC was used for the cast-in-place concrete deck and the prestressed concrete beams. A total of 40 long-gage (2m long) deformation sensors, along with thermocouples were installed in parallel pairs at the top and bottom flange of the girders. The embedded sensors measured temperature and deformations at the supports, at quarter spans and at mid-span. Measurements were collected during:

- Beam Fabrication
    - Casting of the beams
    - Steam curing
    - Strand release
    - Storage
- Bridge Construction
- Service

The data collected was analyzed to calculate the prestress losses in the girders, compare the losses to the predicted losses using available code methods, and get a better understanding of the properties and behavior of high performance concrete.

The project is funded by the Federal Highway Administration, the New Mexico State Highway and Transportation Department, and the National Science Foundation.

INTRODUCTION

In 1987, the Strategic Highway Research Program (SHRP) was initiated to explore products that would improve the constructability of the nation's highways and bridges while minimizing their maintenance. From their search emerged the development of High Performance Concrete (HPC), which is designed to have a higher strength and a durability exceeding that of conventional concrete. The principle ingredients are the same, but by manipulating the mix design with special additives, a "new and improved" concrete can be achieved. Three key mineral admixtures used in HPC are silica fume, fly ash, and slag, which fill air voids and produce a denser and more durable concrete.

Using HPC in prestressed concrete girders has enabled engineers to design bridges with longer span lengths and fewer supports, shallower sections, and increased girder spacing, which can decrease the fabrication, transportation, and erection costs of the bridge. However, despite these benefits, there are other factors that need to be considered. In particular, the design of a prestressed concrete girder is dependent on the amount of prestress loss expected over a period of time. The prestress force in a prestressed concrete girder under service conditions can be significantly lower than the initial jacking force because of prestress losses due to elastic shortening, shrinkage, creep and relaxation. Accurate prediction of the losses is a very important step in the design of a highly stressed HPC girder, and can affect the service behavior of the girder, such as deflections, camber, and cracking of the girder. Current methods for calculating prestress losses according to the American Association for Highway and Transportation Officials (AASHTO) (*1*), and the Prestressed Concrete Institute (*2*) were developed for conventional concrete with 28-day strength up to 41.3 MPa (6,000 psi). Actual prestress losses in HPC girders need to be measured and compared to the predicted losses using these equations.

To date there has been a limited number of full-scale field studies conducted to determine the long-term behavior of prestressed HPC beams.

In a recent study by Li et al at the University of Delaware *(3)*, three HPC bridge girder beams were monitored. Prestress losses were calculated from the measured strains and compared with the predicted values found from the PCI and the AASHTO code. They found that the equations yielded relatively accurate predictions for long-term prestress losses. Furthermore, it was found that the elevated temperature during curing caused noticeable prestress losses that were recovered when the temperature returned to ambient levels.

Byle et al *(4)* at the University of Texas at Austin instrumented and monitored twelve full-scale HPC Texas type U54 bridge beams. Time dependant deflection, camber and strains were measured from transfer of the prestressing force until 5 months after completion of the composite deck. It was reported that the AASHTO and PCI methods yielded inaccurate predictions, with both methods overestimating actual prestress losses.

Roller et al *(5,6)* at Tulane University fabricated four 21.3 m (70 ft.) pretensioned, prestressed high strength concrete bulb-tee girders. Prestress losses at 28 days were found to be 9.6%, which was significantly less than predicted by the AASHTO Standards method and the PCI general method. According to the provisions, a 15% loss was expected within the first 28 days. There were also indications that the steam cure used for one of the girders (Girder 3) may have resulted in extraordinarily low measured prestress loss. At 12 months Girder 3 had an average total prestress loss 50% less than predicted by the AASHTO provisions. When compared to Girder 4, which was not steam cured, the prestress losses in Girder 3 were significantly lower than those in Girder 4. It was concluded that the AASHTO provisions for calculating creep and shrinkage losses might be overly conservative for high strength concrete.

Barr et al *(7)* at the University of Washington investigated the long-term behavior of a HPC pretensioned concrete girder bridge. The data indicated that both the PCI and AASHTO methods predicted lower relaxation and elastic shortening losses than those observed for the girders. The measured creep and shrinkage losses were 0- 32% higher than the losses calculated by the PCI method and were 21% lower to 19% higher than those calculated using the AASHTO method. Overall, the total prestress loss was under-predicted for 4 of the 5 girders reported.

At the University of Minnesota, Alborn et al *(8)* investigated the transfer lengths, camber, prestress losses, and fatigue life of two long-span prestressed bridge girders. The prestress losses were measured and predicted using the Naaman time-step method. The measured prestress losses were found to be slightly higher than those predicted at release. However, at deck casting Girder I exhibited higher losses while Girder II exhibited lower losses than those predicted.

The research results to date show a need for a better, clearer understanding of long term behavior of HPC. Further research is needed to evaluate the current empirical equations and possibly modify them to provide an accurate estimate of prestress losses for a HPC girder.

Furthermore, an understanding of the effects of high temperatures used during steam curing needs to be developed.

The Rio Puerco Bridge is the first bridge to be built in New Mexico with a high performance concrete mix. The purpose of the research study was monitoring the long-term behavior of the HPC girders. Fiber optic deformation sensors were embedded in four of the girders to monitor their behavior for one year following casting of the beams. The objectives of the study were to:

- Determine in-situ mechanical properties of the HPC using the built-in monitoring system
- Compare the losses calculated to those estimated by empirical equations

BRIDGE DESCRIPTION

The Rio Puerco Bridge on Route 66 is located 15 miles west of Albuquerque, NM. The bridge is a 3 span, prestressed concrete bridge as seen in Figures 1 & 2. It is designed to be simply supported for dead load and continuous for live load. High Performance Concrete (HPC) is used for the cast-in-place concrete deck and the prestressed concrete beams. Normal strength concrete is used for the substructure portion of the bridge.

The primary members of the bridge consist of four I-beam type BT-1600. The beams are prestressed by 42, Grade 270 steel tendons: 26 straight and 16 draped. The 12.7 mm (0.5 in.) diameter tendons are 7-wire, low-relaxation strands and are designed for an initial prestress force of 137.8 kN per strand (30.98 kips per strand), slightly overstressed to 146.8 kN per strand (33 kips per strand) to compensate for anchorage losses. The beam cross-sections can be seen in Figure 3.

MONITORING SYSTEM

Four beams labeled AW, AC, BW and BC were monitored in the west and center spans as shown in Figure 4. To measure the prestress losses, strain was monitored in the concrete. Long-gage (2m long) deformation sensors were installed in the top and bottom flanges of the girders (Figure 3) and the cables were routed thru the top flange to the connection box installed on the web side. Five pairs of sensors were installed in each beam, measuring deformations at supports, at ¼ spans, and at mid-span for a total of 40 fiber optic sensors.

To account for temperature strain, thermocouples were installed at the supports and mid-span of each beam at the same location as the fiber optic sensors.

The Fiber Optic Sensors

The fiber optic sensors are deformation sensors manufactured by the Smartec co. The measuring system is based on the principle of low-coherence interferometry. Infrared radiation of light is sent into a single mode fiber and directed towards two fibers through a coupler. The fibers are installed inside the structure to be monitored. The "measurement" fiber is mechanically affixed to the structure and will follow its deformations in both elongation and shortening. The "reference" fiber is installed freely within the same tube. The difference in the length between the measurement fiber and the reference fiber can be measured to give the actual deformation in the structure. When subjected to temperature changes, both fibers expand or contract; therefore, the sensor itself does not need to be temperature compensated.

The long gage (2m) fiber optic sensors were selected because of the following specified properties:

- High resolution: 2μm (79μin)
- Embeddable or surface mountable
- Insensitive to corrosion and vibrations
- Immune to electromagnetic fields
- No calibration required
- Waterproof
- 2 m (6.6 ft) length which provides an average strain measurement in the concrete

Sensor Installation

The beams were prefabricated at CSR Prestress in Albuquerque, NM. The installation of the sensors in the four beams took place on July 17-25, 2000. The four beams were fabricated simultaneously on one long fabrication bed. The bed layout is shown in Figure 5. The cables were extended internally to an outlet 1m from the marked end of each beam, and routed thru the top flange to a connection box installed on the beam web.

MEASUREMENTS

Measurements from the deformation and temperature sensors are read by a 64 channel reading unit. Casting of the beams took place on July 17, 2000. The strands were released on July 24. Following release, the beams were stored for a month at the prestressing plant. On August 26 the beams were transported to the site. The deck was poured one month later on September 26. Measurements were collected during:

- Casting of the beams
- Steam curing
- Strand release
- Storage of the beams, up to transport
- Casting of the slab
- The full year following construction

Measurements were collected continuously during casting, steam curing and strand release. Following release the beams were stored in the casting yard, and data was collected 4 times a day. The beams were then transported to the site, where construction was on going. Monitoring was started again the week prior to deck casting. The bridge was monitored continuously during casting of the deck. Following deck casting, the measurements are collected daily. The equipment is currently programmed to automatically collect data four times a day: at 4:00 am, 10:00 am, 4:00 pm and 10:00 pm.

Sample Data

The values read from the data acquisition system were transferred into an Excel program where the data could be processed and graphed. Figure 6 shows a typical plot of deformation versus time for the deformation sensor in beam AC.

MATERIAL PROPERTIES

Mechanical properties of the HPC were obtained using laboratory testing and the data measurements obtained from the embedded fiber optic sensor system.

Concrete Strength

The concrete was designed for a release strength of 48.3 MPa (7000 psi) and a 28-day strength of 68.9 MPa (10000 psi). Cylinders were taken during the pouring of the girders, steam cured alongside the girders and tested in the laboratory. The compressive strength was found to be 50.5 MPa (7325 psi) at 3 days (strand release), 62.6 MPa (9076 psi) at 28 days, and 70.0 MPa (10151psi) at 56 days.

Coefficient of Thermal Expansion

The coefficient of thermal expansion (α) is defined as the change in unit length per degree of temperature change. The change in length due to a change in temperature is given by:

$$\Delta L = \alpha L(T - T_0) \qquad (1)$$

where L = original length
$T - T_0$ = Temperature change
α = Coefficient of thermal expansion

During storage, the daily strain fluctuations in the beams are mainly due to the daily temperature changes. To determine the coefficient of thermal expansion, the change in temperature versus the strain in the concrete are measured and plotted, and the coefficient of thermal expansion is calculated (Figure 7). The coefficient of thermal expansion values measured at 7 days and 31 days were 12.5 and 12.7 respectively for an average of 12.6 microstrain/ ^{o}C (7 microstrain/°F). Reported values of the coefficient of thermal expansion for concrete range between 5.8 to 12.6 microstrain/ ^{o}C (3.2 to 7 microstrain/°F), with an average of about 10 microstrain/ ^{o}C (5.5 microstrain/°F)*(9)*. The coefficient of thermal expansion for saturated Portland cement pastes of varying water/cement ratios is approximately 18 microstrain/ ^{o}C (10 microstrain/°F) *(10).* The coefficient of thermal expansion measured is consistent with the high cement paste content in the mix *(11).*

Modulus of Elasticity

The modulus of elasticity (E) of concrete varies with strength, concrete age, loading type, and the characteristics of the cement and aggregates. Using Hooke's law:

$$E = \sigma/\varepsilon \qquad (2)$$

where σ = stress in the concrete
ε = strain in the concrete

E is calculated at two times: at 3 days when the prestressing force is transferred from the steel tendons to the concrete, and at 60 days when the deck is poured. At transfer, the change in stress in the concrete is that caused by the release of the prestressed tendons, and can be determined by the following equation:

$$\sigma = -P/A \pm Mc/I \qquad (3)$$

where P = Jacking force
A = Transformed cross-sectional area
M = Moment caused by prestress = P * e
e = Distance from steel centroid to transformed section centroid
c = Distance from the transformed section centroid to the location sensor
I = Moment of inertia of the transformed section

The strains are calculated for the bottom sensors at midspan of each beam and compensated for temperature using the following equation:

$$\varepsilon_{non\text{-}thermal} = \varepsilon_{raw} - \alpha_{concrete}\,\Delta T \qquad (4)$$

where ε_{raw} = raw strain
$\alpha_{concrete}$ = average coefficient of thermal expansion determined as 12.6 x 10^{-6} microstrain/°C
ΔT = change in temperature measured by thermocouples

The modulus of elasticity at 60 days is calculated using the stresses and strains that occur in the concrete when the deck is poured. When the deck is poured, the change in stress is caused by the addition of the weight of the slab:

$$\sigma = M_{slab}\, c / I \qquad (5)$$

where M_{slab} = Moment at midspan due to weight of the slab
c = Distance from the transformed section centroid to the location of the sensor
I = Moment of inertia of the transformed section

The change in strain in the concrete is determined from the change in the sensor measurements when the slab was poured. The strains are calculated and compensated for temperature.

Section 8.5 of the ACI Code *(12)* states that the modulus of elasticity for normal weight concrete can be taken as:

$$E = 57{,}000\,(f'c)^{1/2}\ \text{psi} \qquad (6)$$

The expression recommended for computing E for high-strength concrete by ACI Committee 36 *(13)* is:

$$E = 40{,}000\,(f'c)^{1/2} + (1\text{x}10^{6})\ \text{psi} \qquad (7)$$

As seen in Table 1, ACI equation (6) gave a very close estimate of what was measured in the field. Overall, all three values obtained from the field and from the empirical equations were found to be reasonably close.

PRESTRESS LOSSES

Four methods where used to predict the prestress losses: the Prestressed Concrete Institute (PCI) General Method *(2)*, the American Concrete Institute – American Society for Civil Engineers (ACI-ASCE) Method *(14),* the AASHTO LRFD Refined Method *(1),* and the AASHTO LRFD Lump Sum Method *(1).* None of these methods were developed specifically for High Performance Concrete.

The PCI General Method is a time-step method, and therefore permits calculation of prestress losses at specific time intervals. Using the PCI General Method, the incremental prestress losses can be calculated and compared to the stresses measured by the sensors during that time interval. It also requires input of material properties.

The ACI-ASCE and the AASHTO LRFD refined methods are component methods, where the individual components of losses due to elastic shortening, creep and shrinkage of concrete, and relaxation of the steel are computed based on a knowledge of material properties and summed together for an estimate of the total loss.

The AASHTO LRFD Lump Sum method provides a simple approach. It uses a single equation to calculate the ultimate loss. The equation to be used depends on the beam section type and the type of prestressing.

Prestress losses measured in the field were compared to losses predicted by these four methods. All strain measurements were compensated for temperature. The in-situ material properties determined in the field were used to calculate the prestress losses.

PCI Method vs. Field Measurements

The PCI General method was used to calculate the early prestress losses that occurred at:

- Transfer of the prestressing force (strand release)
- One month after transfer
- The cumulative losses were calculated for one year after transfer.

As illustrated in figure 8, it was found that:

- The PCI method slightly over predicted the prestress loss at transfer.
- The PCI method over predicted the prestress loss during the month of storage following fabrication by a large margin. The PCI method predicted large losses due to creep during that first month. The high performance concrete showed much less creep than factored in the PCI equation.

Comparing Total Losses: measured vs. predicted

In Figure 9, the measured prestress losses (up to one year from beam casting) are compared to the total losses estimated by each method. The losses are expected to taper off over the next few months. The predictions of the four methods are relatively similar. The PCI method is a complex, time-step method for predicting the prestress losses. On the other hand, the AASHTO LRFD Lump Sum method is very simple to use, requiring little calculations. The AASHTO LRFD Lump Sum predicted an average loss close to that of the PCI method. The AASHTO LRFD method predicted the most losses, and the ACI-ASCE method predicted losses somewhere in the middle. The LRFD Lump Sum method offered a quick estimate that was quite close to the refined PCI General method estimate. Overall, all methods are found to be very conservative. The prestress losses measured are 13% vs. 22 % predicted by the PCI general method.

EFFECTS OF STEAM CURING TEMPERATURE

Beam AC was steam cured at a lower temperature than the other three beams. The highest temperature measured for beam AC was 70 vs. 90 ^{o}C (158 ^{o}F to 194 ^{o}F **)** for the other beams. Figure 10 shows a plot of temperature vs. time for the beams.

It was found that beam AC exhibited much larger prestress losses than the other three beams in the month following transfer as shown in figure 11:

- Prestress losses measured one day after transfer in beam AC were about 3 to 6 times the losses measured in the other beams as can be seen in figure 11a.
- Prestress losses measured during the storage month following transfer in beam AC were about 1.5 times the losses measured for the other beams, as shown in figure 11b.
- This pattern of much larger losses for beam AC is most pronounced in the month following transfer, and tapers off with time, as shown in figure 11c.

CONCLUSIONS

A built-in monitoring system was used successfully to monitor a bridge during fabrication and construction. Monitoring the beams during the fabrication process gave an insight into the effect of the steam curing temperature**.** Material properties and prestress losses were measured using the built-in sensor system. Based on the research conducted in this project, the following conclusions can be drawn:

1. In this project the current code methods are found to over predict the prestress losses for steam cured HPC. There is a need to modify these methods or develop new ones to better predict prestress losses for HPC.

2. Estimates by all four methods, the complex time consuming PCI general, the ACI-ASCE, the AASHTO LRFD refined, and the simple AASHTO LRFD Lump Sum, came within a close range. Overall, all four methods over predicted the prestress losses for HPC and are found to be very conservative.
3. HPC exhibited much less creep in the month following transfer than factored by the PCI general method.
4. The steam curing temperature can have a significant effect on the early prestress losses in HPC. A lower curing temperature was associated with larger early prestress losses following transfer. This is most pronounced in the month following transfer, and tapers off with time.
5. An embedded monitoring system can be used successfully to measure the in-situ material properties of the concrete.
6. The coefficient of thermal expansion measured was towards the higher values of its reported range, which is consistent with the high cement paste content of the concrete mix.
7. The modulus of elasticity calculated from beam measurements in the field compared well to the value calculated using the ACI code equation recommended for normal weight concrete. Overall, the ACI code normal weight equation, the ACI 36 modified formula for high strength concrete, and the field measurements were reasonably close.
8. This research project identified the need to improve the methods of predicting prestress losses for HPC. Further research is needed to investigate the effects of mix design, curing temperature, and beam type on prestress losses.

ACKNOWLEDGMENTS

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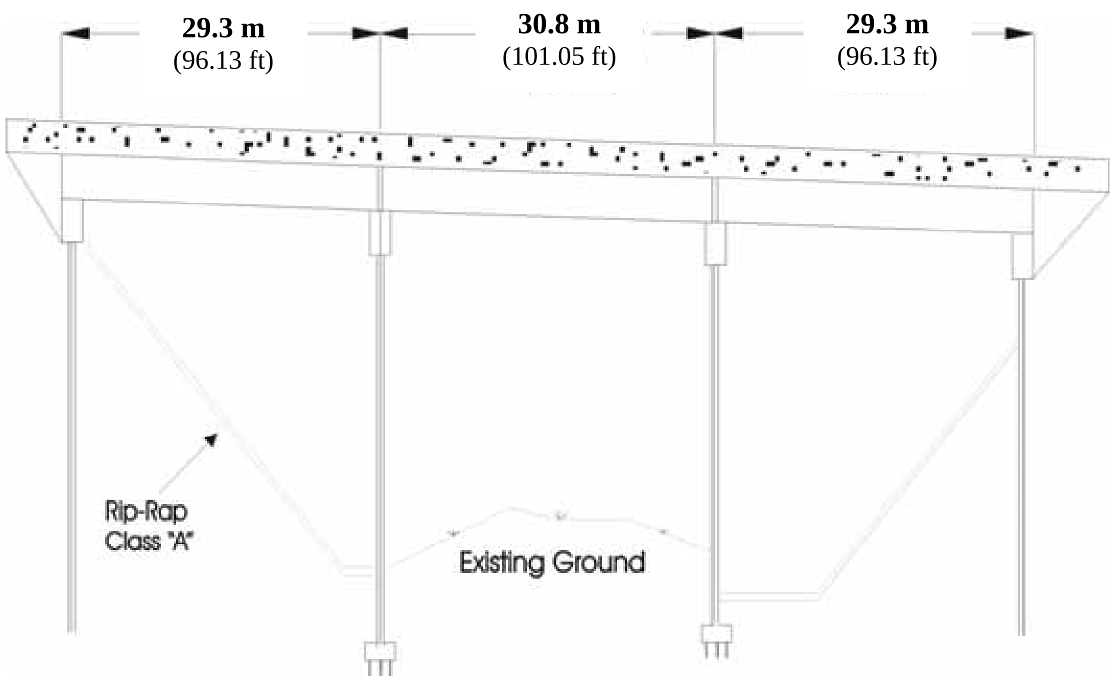
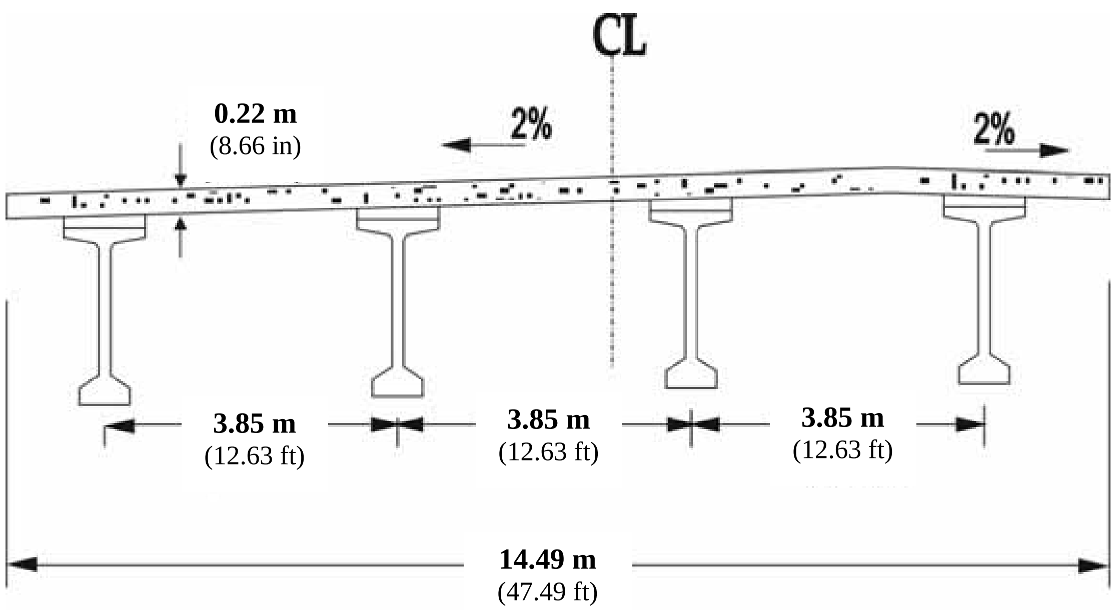
Table 1. Modulus of Elasticity: Empirically determined compared to calculations from field data

Modulus of Elasticity	Expected in design	Calculated from field data	Empirically determined (Eq.6)	Empirically determined (Eq.7)
	MPa	MPa	MPa	MPa
3 days	35,000	34,159	33,636	30,499
60 days	42,000	39,247	39,594	34,683

Figure 1. View of the Rio Puerco Bridge



a. Bridge profile along centerline



b. Bridge cross-section

Figure 2. Bridge profile and cross-section

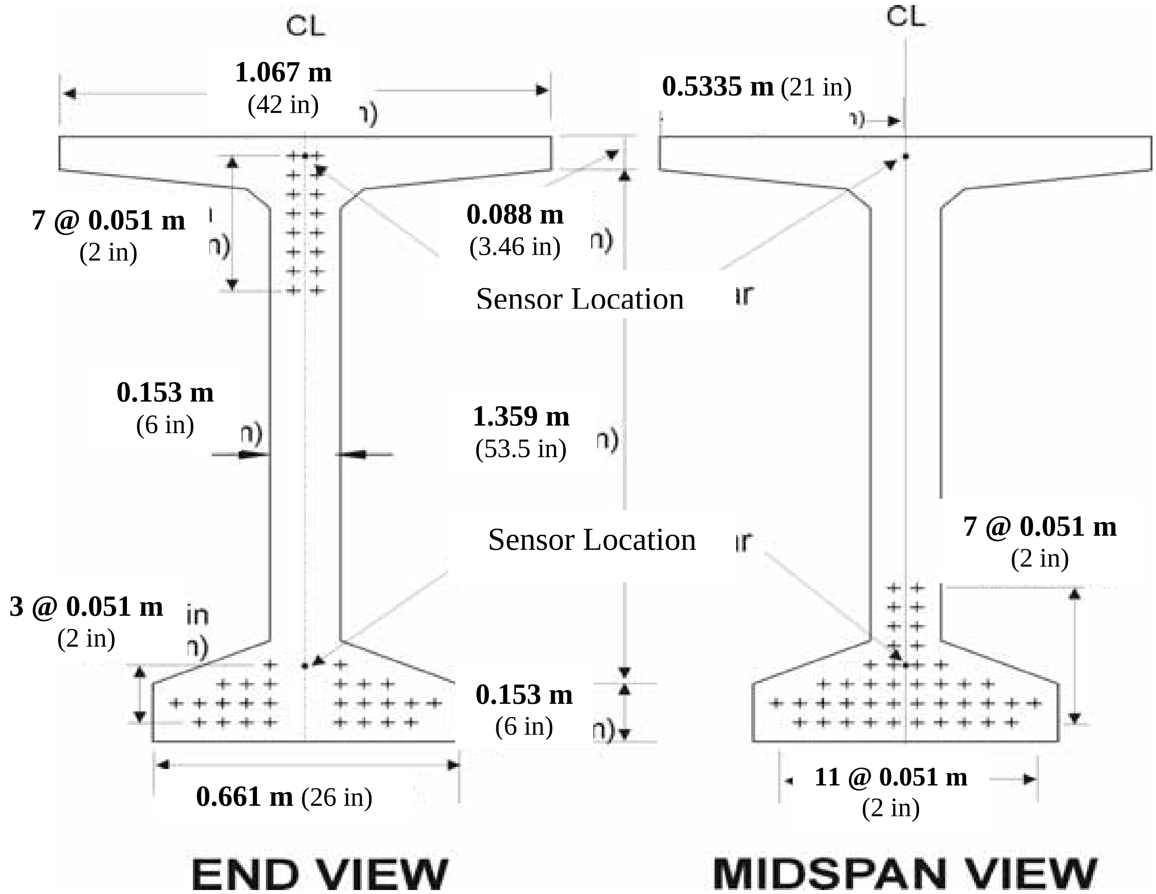
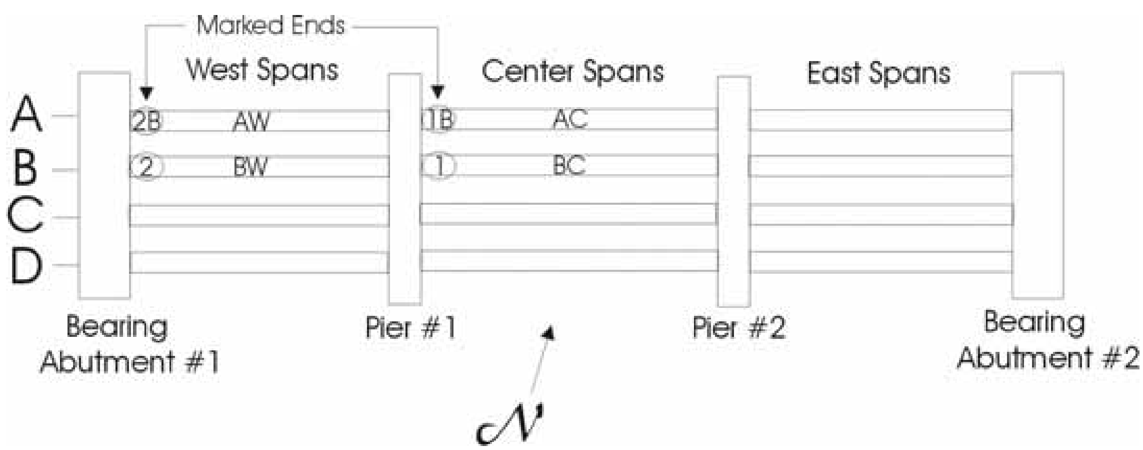


Figure 3. Cross-sectional view of BT-1600 I-beam



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a. Photograph of bed layout

b. Close up of sensor in bottom flange

Figure 5. Sensor installation

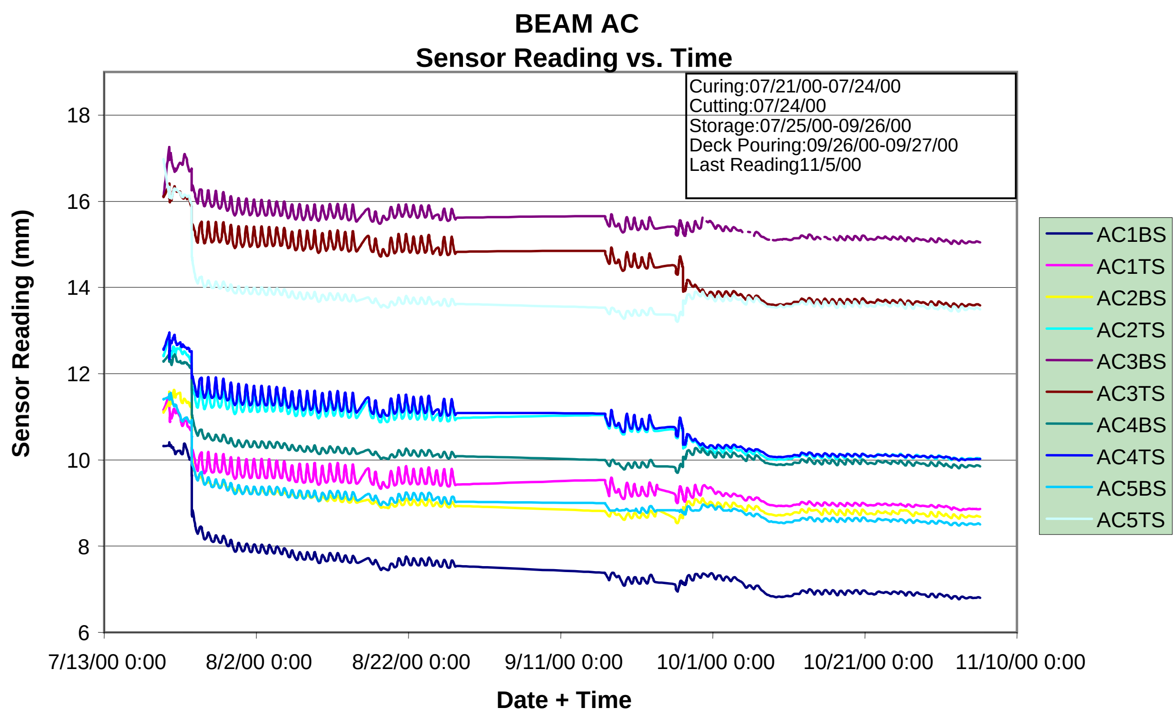
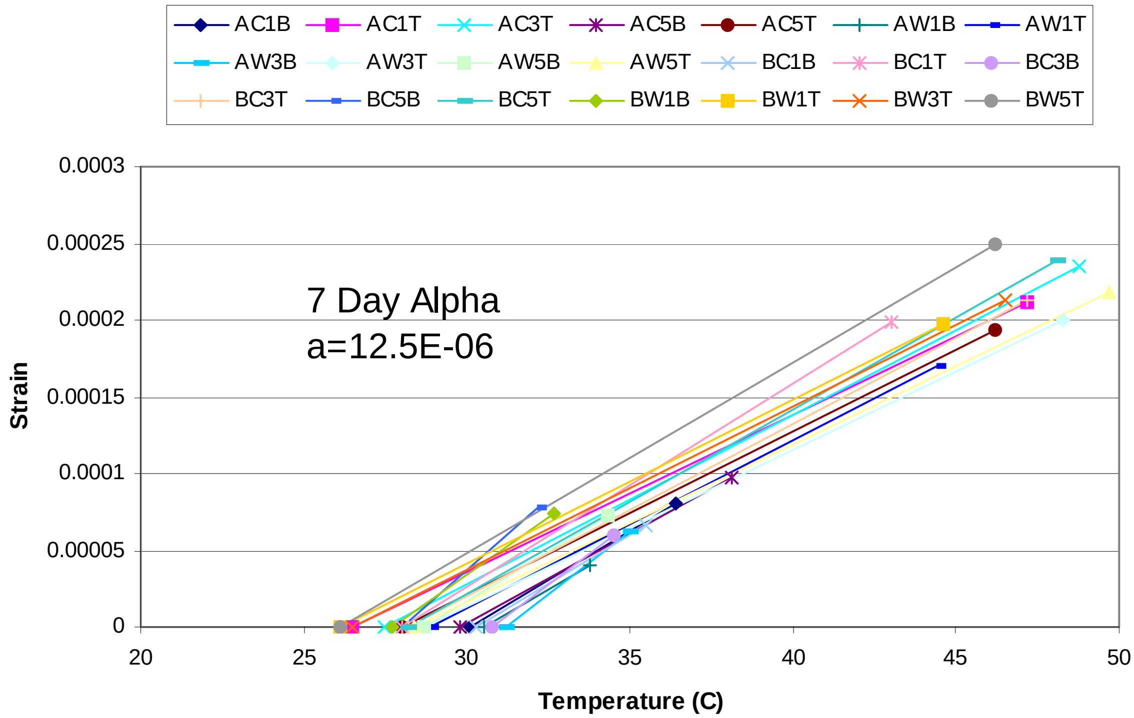
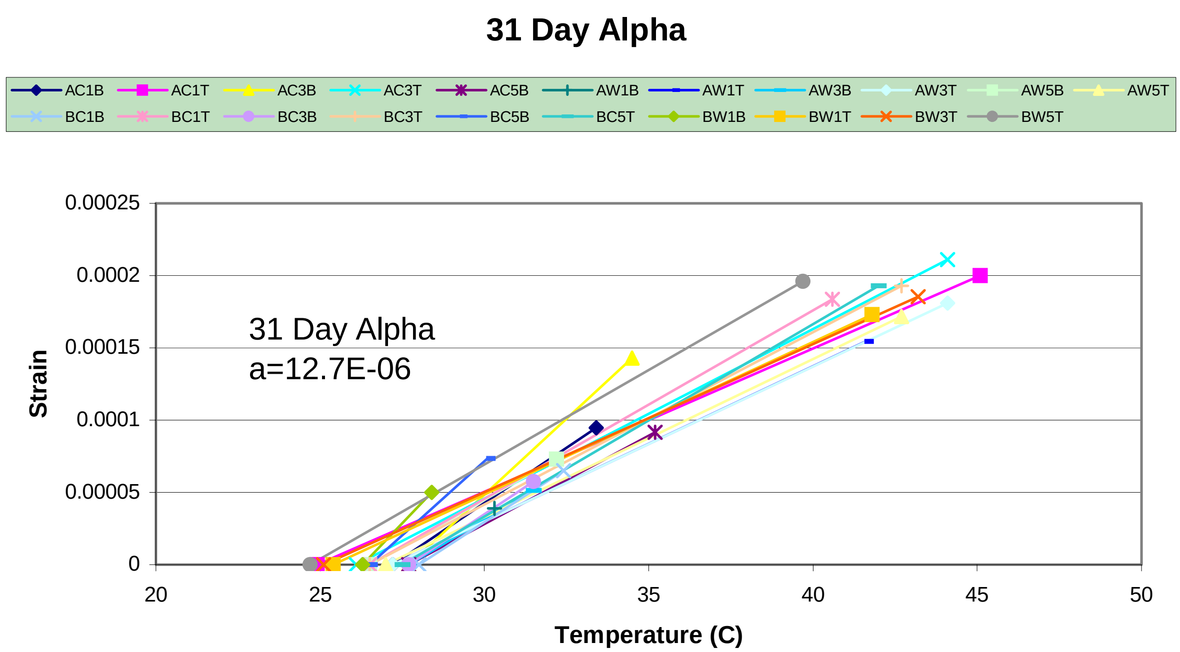


Figure 6. Sensor reading vs. time for beam AC



a. Coefficient of thermal expansion at 7 days



b. Coefficient of thermal expansion at 31 days

Figure 7. Coefficient of thermal expansion at 7 days and 31 days

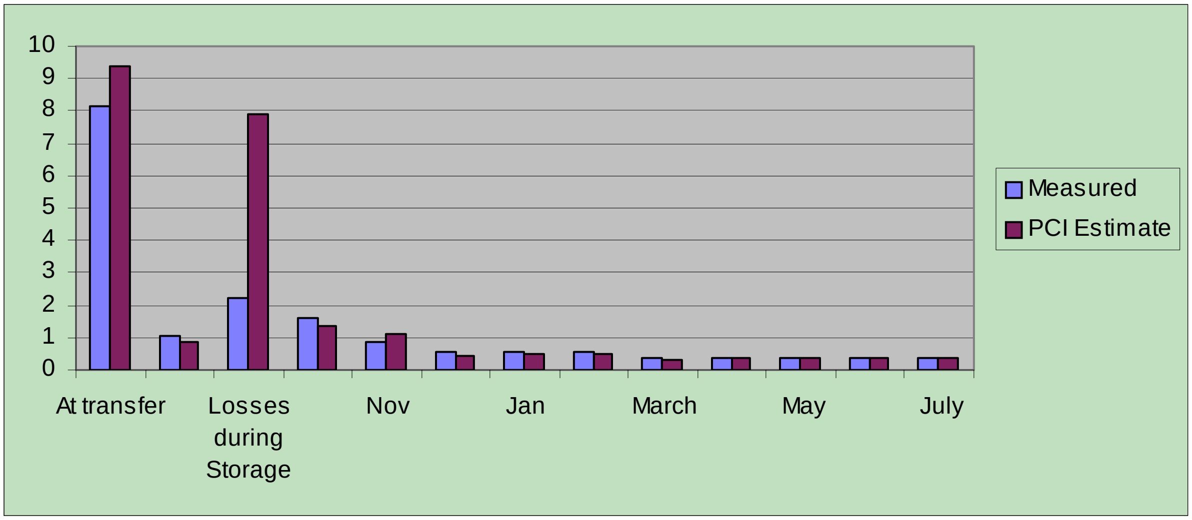


Figure 8. % prestress loss. Field measurements vs. the PCI Method

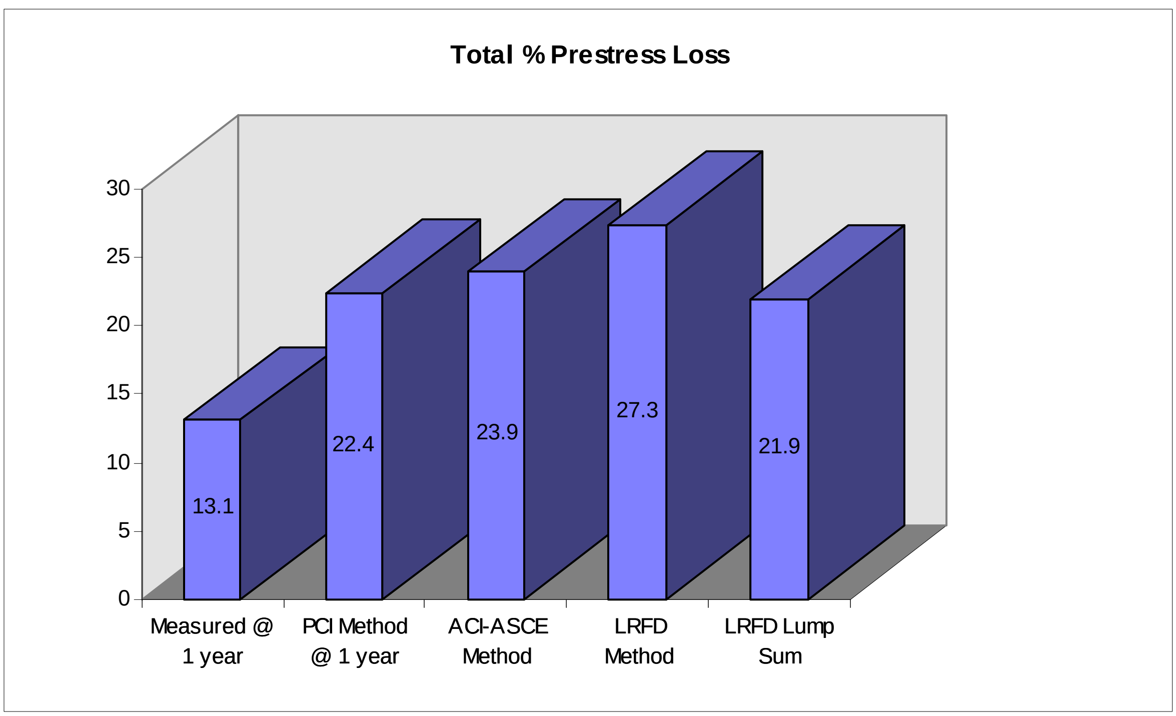
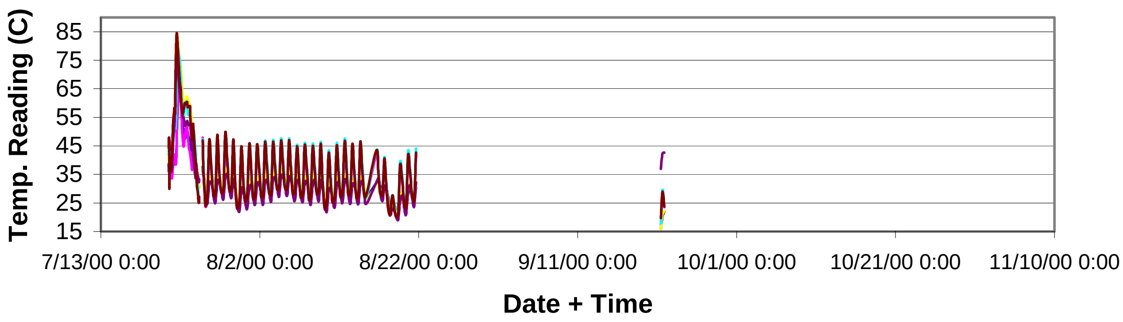
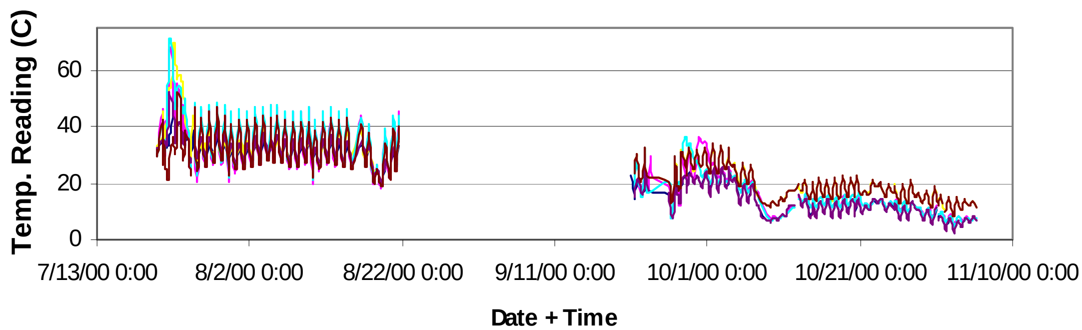
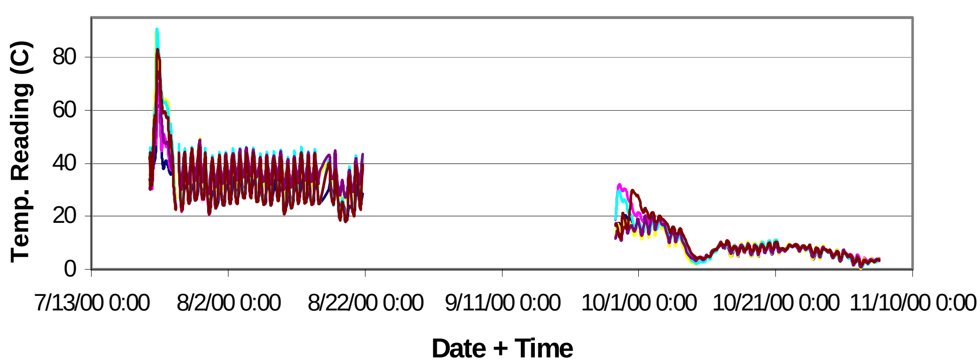


Figure 9. Measured losses vs. losses estimated by various methods

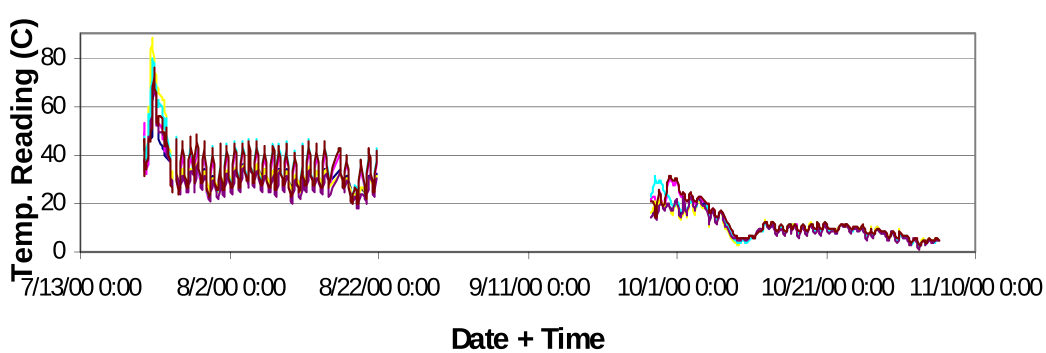


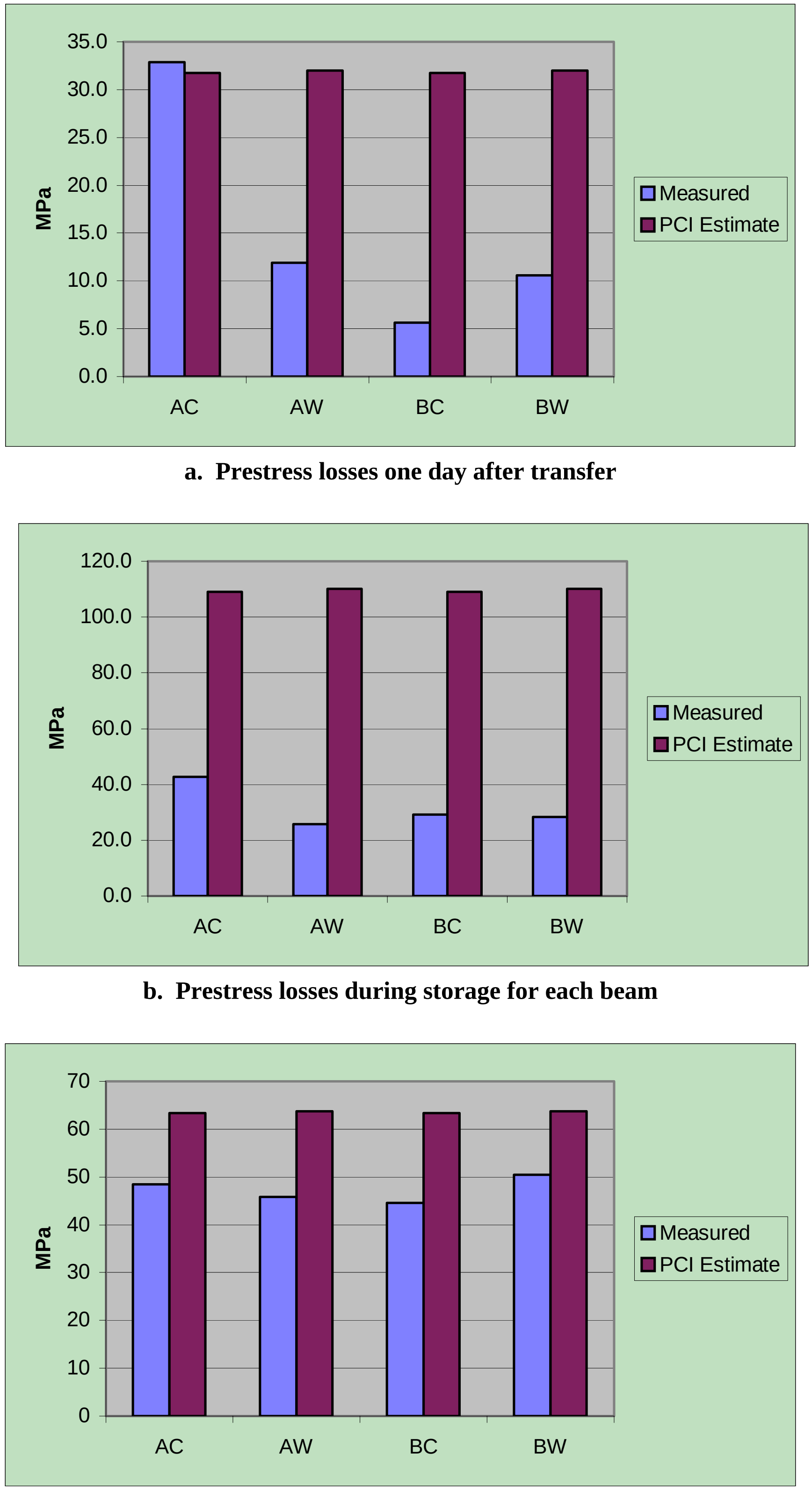


b. Temperature reading vs. time for beam AC



c. Temperature reading vs. time for beam BW





a. Prestress losses one day after transfer

b. Prestress losses during storage for each beam

c. Prestress losses during the 10 months period after deck placement

Figure 11. Prestress losses