

## **ABSTRACT**

Title of Thesis: BEHAVIORAL STUDY OF ULTRA HIGH PERFORMANCE CONCRETE GIRDERS.

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Ultra High Performance Concrete (UHPC) is one of the newer and superior classes of concrete that can be used to develop improved bridges capable of meeting the present and future traffic, environmental, maintenance and economical requirements. Developing on the superior material properties of UHPC, the research discussed herein studies the behavior of UHPC when used as a bridge girder material. Four optimized girders have been cast and studied for various early age as well as long term properties such as early age shrinkage, transfer length, creep behavior and shrinkage under steam treatment. Data has been recorded through vibrating wire gages installed at strategic locations within each girder before they are cast. While the shrinkage and creep observed are very low which is characteristic of UHPC, various other aspects such as shrinkage being closely tied to formwork restraint and temperature and the prestress transfer being dependent on the girder geometry and strand pattern have been discussed. From the results we can conclude that UHPC is a promising bridge building material and with further research can be extensively employed for developing bridges.

BEHAVIORAL STUDY OF ULTRA HIGH PERFORMANCE CONCRETE GIRDERS

By

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## **Chapter 1 – Introduction**

### **1.1 Industrial Context and Purpose of the Project:**

The importance of transportation facilities to the nation's economic strength and efficiency is generally recognized. A fundamental requirement of manufacturers is to distribute their products to appropriate markets quickly and inexpensively; people must be able to get to work and to conduct business. As illustrated by recent disasters - flooding along the Mississippi and Missouri rivers and the Northridge earthquake in California - any significant disruption in the movement of goods or people economically impacts a great number of businesses and huge population groups. The FHWA established a priority research project in 1989 for studying the connection linkage between investment in highways and bridges and the nation's ability to sustain economic performance and growth. The link between transportation and economic development continues to justify significant public expenditures in transportation systems at the local, state, and federal levels.

The benefits from our highway system cross all levels of society and are exhibited in several ways. The industry studies indicate that evolving management forms and logistic cost-savings would not be possible without our expansive highway system. For example, a lower-cost, efficient, reliable highway network allows transportation consumers to redesign production processes and access more markets, thereby providing a wider array of goods and services at lower costs. Reductions in logistic costs will continue to offer consumers and producers extraordinary benefits.

Employing newer and more suitable materials available to the construction industry is an important step towards achieving the above stated objectives. 60% of all US highway bridges are made of concrete, the most commonly adopted material used in the construction of bridges, which makes practical sense that an improved concrete material replace conventional concrete materials as the material of choice. In light of the current state of highway bridge girders today, the Federal Highway Administration (FHWA) is constantly seeking to develop improved bridges that can meet and adapt to current and future traffic, minimize environmental impact, require low-maintenance and are economical and easy to install.

A new class of material that has been developed recently and is capable of achieving such goals is Ultra-High Performance Concrete (UHPC). It exhibits greatly improved strength, exceptional durability and ductility. The UHPC is a new generation of fiber-reinforced cementitious material, an ultra high strength concrete reinforced with organic or steel fibers. It is composed of Portland cement, silica fume, crushed quartz, sand, fibers, superplasticizers and water.

The Federal Highway Administration (FHWA) at its Turner-Fairbank Highway Research Center (TFHRC) is currently evaluating Ultra-High Performance Concrete (UHPC) for use in the transportation industry. It requires less material than ordinary reinforced concrete bridges owing to its considerable mechanical properties. It is more durable and easier to install due to the presence of short fibers randomly oriented throughout the material mitigating the need for reinforcing bars. FHWA's testing of UHPC has revealed

it to be a promising addition to the HPC (High Performance Concrete) currently being used by the bridge construction industry.

## **1.2 Scope of Study and Research Approach:**

The various properties exhibited by the UHPC have been thoroughly characterized by the research undertaken by the FHWA. Building on the available information about the material and its properties, the current phase of the research focuses on behavior of UHPC when used as a bridge girder material.

The first step was the design of the prototype girder section to be used in the current research stage. The design of the model section and the further refinement was done at the Massachusetts Institute of Technology (M.I.T.). Firstly, a two-phase constitutive model for UHPC was created and validated through shear and flexural tests. The optimized shape and section heights of the girder were developed in the preliminary designs. In further designs, the existing cross-sections were refined and new cross-sections with different slab web thicknesses were investigated. Designs of the girders were conducted with the aid of a finite element analysis program that has been verified for UHPC. The designs were assessed against service and ultimate limit state crack-opening criterions. A 2-D model was first analyzed to determine global flexural behavior of the beams, followed by a 3-D model to examine localized strain effects. The result of this work was the final bulbed double-tee prestressed girder section, which was discussed

in subsequent chapters and satisfactorily met all performance criteria under both ultimate and service limit state.

The girder is 70 feet long, 33 inches deep, with an eight-foot wide deck. The cross-section contains 22 to 24 prestressing strands and no mild steel. Four of these girders have been constructed using a 28 ksi compressive strength UHPC. It was planned to use two of these girders for the construction of the bridge at the Turner-Fairbank Highway Research Center. These girders will be periodically tested and monitored for several years to determine the long-term shrinkage and creep behavior of the UHPC bridge as well as the other properties such as long-term deflections and durability. The remaining two girders will be destructively tested to determine the behavior and capacity of this material/girder combination. Also, all the girders were monitored for short-term behavior such as immediate shrinkage, shrinkage under steam treatment, transfer of prestress, short-term creep, camber and other midspan behaviors. It is this part of the early age behavior of the girders that this thesis focuses on.

### **1.3 Structure of the Thesis:**

This thesis is divided into six chapters. The first chapter gives a brief review of the purpose of the project and the scope of the study. In chapter 2, the background information of the material behavior has been underlined; various test results characterizing the properties of UHPC are listed. The experimental program for the project is detailed in Chapter 3, including discussion of the cross-section and the prestressing details for each girder as well as the strain sensitive gages and their

positioning for each girder. The actual preparations and procedures undertaken during casting of the girders are stated in Chapter 4. Chapter 5 presents the results and analysis of the shrinkage, prestress transfer, midspan behavior and creep properties of the girders. Chapter 6 summarizes the findings and feasibility of the UHPC material, which was investigated as a bridge-building material.

## **Chapter 2 – Background Research and Material Properties**

### **2.1 UHPC:**

Ultra-High Performance Concrete (UHPC) is a solution developed to address some of the main design, service life and life cycle costing issues associated with the use of concrete.

Ductal by Lafarge is the Ultra High Performance Fiber Reinforced Concrete used in this research. It is a steel fiber reinforced concrete consisting of an optimized gradation of fine powders and a very low water to cementitious materials ratio. It exhibits enhanced strength, durability and ductility properties when compared to normal concrete or high performance concrete. UHPC in general is steel fiber-reinforced reactive powder concrete that typically displays twice the compressive strength of any High Performance Concrete (HPC) used in United States bridge construction. The French firm Bouygues SA developed the reactive powder concrete originally, which is engineered to be a highly compacted concrete with a small, disconnected pore structure that helps to minimize many of the limitations of typical HPCs. These advancements are achieved through a combination of finely ground powders and the elimination of coarse aggregates. The addition of small steel fibers to the mix is responsible for much of the tensile strength and toughness of the material. These fibers eliminate the need for mild reinforcing steel in the girders and knit the material together after cracking has occurred. The placement and curing of UHPC can be performed using procedures similar to those already established for use with some HPCs. The fluid mix is virtually self-placing and requires no internal vibration. If required, external form vibration causes the mix to flow smoothly into place.

Following an initial set of 24 hours, the curing process requires at least an additional 48 hours, including a vapor bath at a constant 88 °C (190 °F). Hence it is available for loading within a period of 3 days as compared to almost 30 days in the case of normal concrete.

Table 2.1 enlists the various constituents of the UHPC used for the girders, which are more or less the same as other concretes except for the proportions. Glenium 3000 NS was the superplasticizer recommended by UHPC premix manufacturer Lafarge, while Rheocrete CNI was recommended as the accelerator. The steel fibers were 0.2 mm in diameter and 13 mm. in length and were added at a ratio of 2% by volume.

Table 2.1 UHPC Composition.

Material	Amount (lb/yd <sup>3</sup> )	Percent by Weight (%)
Portland Cement	1200	28.5
Fine Sand	1720	40.8
Silica Fume	390	9.3
Ground Quartz	355	8.4
Superplasticizer	51.8	1.2
Accelerator	50.5	1.2
Steel Fibers	263	6.2
Water	184	4.4

It can be seen that the amount of water is very small, in comparison to the large amounts cementitious materials and superplasticizers. The ratio of water and accelerator to cementitious material (i.e., cement and silica fume) is 0.15.

Numerous other countries already employ UHPC in different structural applications. Canada and South Korea have used UHPC for pedestrian bridges: the Sherbrooke Bridge in Quebec, Canada, built in 1997, a pedestrian bridge of 190 ft. with a deck thickness of only 1.25 in.; and the footbridge of Peace in Seoul, Korea, built in 2002. The span of this bridge is 400 ft. and its deck thickness is 1.25 in. Portugal has employed it for seawall anchors, Australia has committed to its use in a vehicular bridge, and France has used it in building power plants. In all of these cases, the material was chosen for its ability to stand up to high stress, both environmental and load-related. The increasing deployment of UHPC worldwide and results of FHWA's testing the product bode well for its future use.

## **2.2 Material Properties of Interest to Project:**

The research conducted at the Turner-Fairbank Highway Research Center has provided a thorough characterization of the material properties exhibited by UHPC. The various tests conducted on UHPC can be classified into Strength testing and Durability testing. The strength tests carried out were compressive strength, modulus of elasticity, split-tension, direct tensile strength, mortar briquette, flexural toughness, fatigue, shrinkage and creep. The durability tests were freeze-thaw resistance, scaling resistance, abrasion resistance, chloride penetration, alkali-silica reaction and air voids. Other tests were heat



of hydration, fiber dispersion (by optical and tomographic methods) and ultrasonic properties (cracking inspection and modulus determination).

The curing of UHPC can have a significant effect on its properties and hence the research at FHWA has been done with UHPC cured using four different regimes. The Steam curing regime (194°F, 95%RH) involves steam curing for 48 hours beginning soon after stripping of the molds. The Ambient Air curing regime, allows the specimens to remain in an ambient laboratory environment from casting until testing. The Tempered Steam curing regime (140°F, 95%RH) lasts 48 hours after stripping but involves lower temperature steam. The final curing regime is the Delayed Steam cure, which is similar to the first regime, except that the process is delayed until 15 days after casting.

The various properties of UHPC that have been characterized and are of use to the UHPC girder research are briefly described below:

### **2.2.1 Compressive Strength:**

Cylinders of diameter 3 in. and length 6 in. were tested for determining the compressive strength of UHPC. Testing was done in accordance with ASTM C39 except that the load rate was changed to 150 psi/sec so that the failure load was reached in a reasonable time.

The 28-day strength results for various curing regimes are given below in Table 2.2.

Table 2.2 Compressive Strength of 3 x 6 in. UHPC cylinders.

Curing Method	Compressive Strength (ksi)
Steam	28.0
Ambient Air	18.0
Tempered Steam	25.2
Delayed Steam	24.9

**2.2.2 Tensile Strength:**

It was observed that UHPC exhibited significantly higher tensile strength, both before cracking and after cracking. It has various advantages such as higher precracking tensile load-carrying capacity as well as stiffer post-cracking sections. Various tests, such as mortar briquette tension test, direct cylinder tension test and split cylinder tension test, were conducted to quantify the tensile strength of UHPC. Table 2.3 shows some of the direct tensile cracking strength results obtained for different regimes.

Table 2.3 Direct Tensile Cracking Strength of UHPC

Curing Method	Cracking Strength (ksi)
Steam	1.60
Ambient Air	0.82
Tempered Steam	1.14
Delayed Steam	1.62

### **2.2.3 Shrinkage:**

In a limited shrinkage study based on ASTM C157, 1 in. by 1 in. UHPC bars with 11 in. length were cast and cured. The initial reading was taken immediately after stripping of the molds, while the final reading was taken after the curing procedure had been completed, or at 28 days for the Ambient Air-cured specimens. Table 2.4 shows the results of the shrinkage tests.

Table 2.4 Shrinkage of UHPC Bars

Curing Method	Shrinkage (%)
Steam	0.047
Ambient Air	0.062
Tempered Steam	0.025
Delayed Steam	0.050

The Center's Structures Laboratory also tested two American Association of State Highway and Transportation Officials (AASHTO) Type II prestressed concrete girders fabricated from UHPC. The tests were intended to characterize the girder's structural behavior and determine how well the current AASHTO design provisions represent that behavior.

The structural test of the first girder delivered some impressive results. Just prior to failure, the 80-ft long girder displayed a mid-span deflection of more than 19 in. Even more impressive was the girder's ability to sustain a large load and associated deflection

without creep, relaxation, or any visual sign of distress. For example, the flexural test was suspended for more than 12 hours with 12 in. of mid-span deflection locked into the girder. During that time, the girder was unchanged, and even with the aid of a 3x magnifying glass no cracks were detectable.

Three additional structural tests designed to determine the shear capacity of the UHPC girders have been completed. These tests revealed that the shear capacity of a UHPC girder without shear reinforcement is approximately two to three times that of a conventionally reinforced prestressed concrete girder.

## Chapter 3 – Experimental Program

### **3.1 Introduction:**

This chapter covers the experimental program and instrumentation setup for the UHPC girders. First, it describes the details of the optimized cross-section and prestressing scheme for each girder, followed by a description of the strain sensitive equipment and measuring instruments used for capturing the behavior of the girders. The next section gives an outline of the gage identification scheme and the gage positioning for each of the girders.

### **3.2 Girder Geometry:**

Figures 3.1 and 3.2 show the details of the girder section and the prestressing strand layout. The 70-ft. span UHPC girder has a double-T shaped profile and a total depth of 2 ft. 9 in. The deck slab is 8 ft. wide and 3 in. deep with edges thickened to 6 in. for bolted and welded connections on either side. The webs are 3 in. thick at the deck and taper to 2 in. at the bulbs. The bottom flange is formed of bulbs projecting to the outside from each web. Each of the bulbs is 7 in. thick and 11 in. wide. Prestress is applied through eleven- $\frac{1}{2}$  in. diameter, 270 ksi low relaxation strands placed symmetrically in each bulb. Of these strands, 6 are fully bonded throughout the girder span, 3 are debonded to 12 in. from either end, and 2 are debonded to 72 in. from either end. The applied prestressing force is 29.2 kips in each strand. In the third and fourth girders, there is an additional strand (carrying a prestressing force of 29.2 kips) located at the center of the junction of

the web and the deck. In the west end of the fourth girder, the three interior strands have been draped in each bulb and the 12 in. debonds have been eliminated.

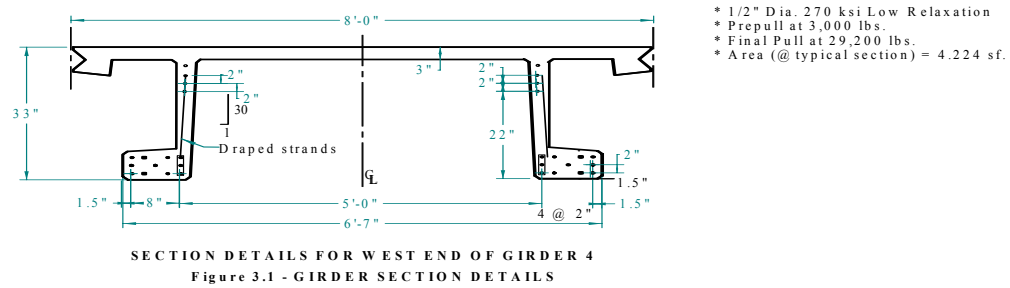
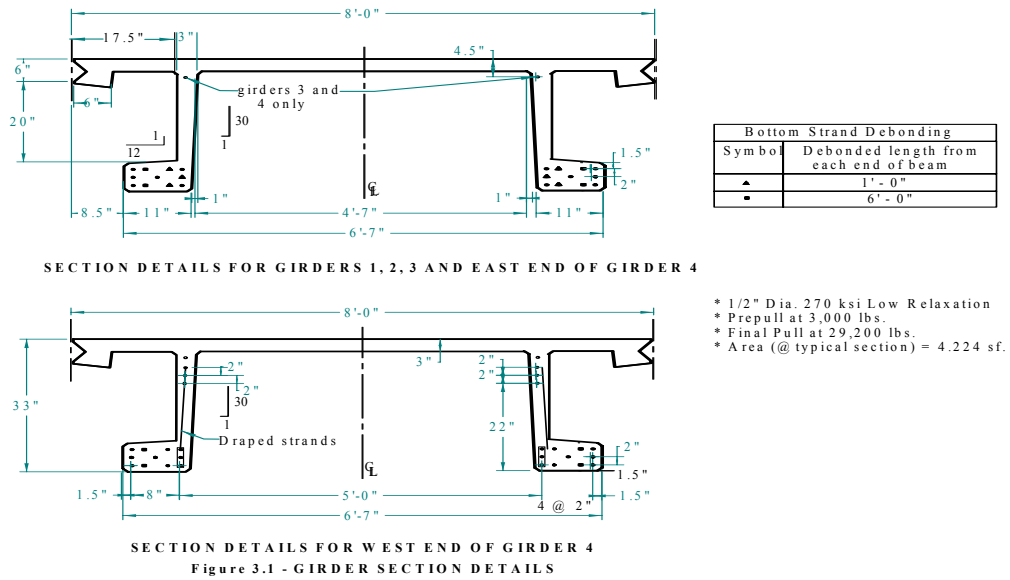


Figure 3.1 - GIRDER SECTION DETAILS

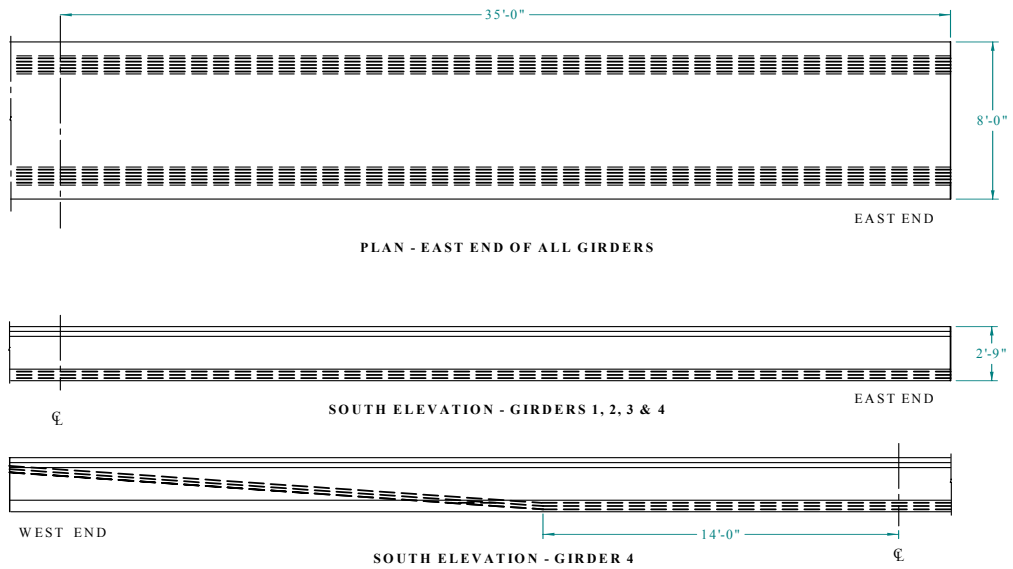


Figure 3.2 - GIRDER LONGITUDINAL DETAILS

### **3.3 Instrumentation:**

Vibrating wire gages were used to capture the internal strain behavior of the girder. In total, 44 Geokon vibrating wire gages were cast into the four girders. These gages are 2 in. in length. Strains are measured using the vibrating wire principle in which a tensioned wire will vibrate at different frequencies depending on its strain. In this case, a length of steel wire is tensioned between two end blocks that are embedded directly in concrete. The deformations of the concrete mass cause the two end blocks to move relative to one another thus altering the tension in the steel wire. The tension is measured by plucking the wire and measuring its resonant frequency of vibration using an electromagnetic coil.

These gages have excellent long-term stability, excellent resistance to the effects of water, and a frequency output suitable for transmission over very long cables. Each gage also incorporates a thermistor so that the thermal state of the concrete near the gage can be monitored. The gages were monitored through a readout box which, when connected to an individual gage, would provide the associated strain and temperature values.

### **3.4 Instrumentation Plan:**

The instrumentation plan for the girders is detailed below. The gages have been located so as to capture data representative of uniform flexure, transfer, creep, and shrinkage behaviors. The gages are sensitive to the changes in concrete strains and changes in temperature. Note that the strain value provided by the gage is assumed to be the strain in the concrete at the center of the gage length.

The instrumentation plans for the girders show the locations of the strain gages in each girder. The locations of the gages vary with each girder as changes have been made with progressive analysis so as to capture the most data from the overall set of girders.

Each of the gages is labeled by an alphanumeric character string. This identifier contains six characters and indicates the gage's location within the girder. Figure 3.3 provides the description of the gage identifier.

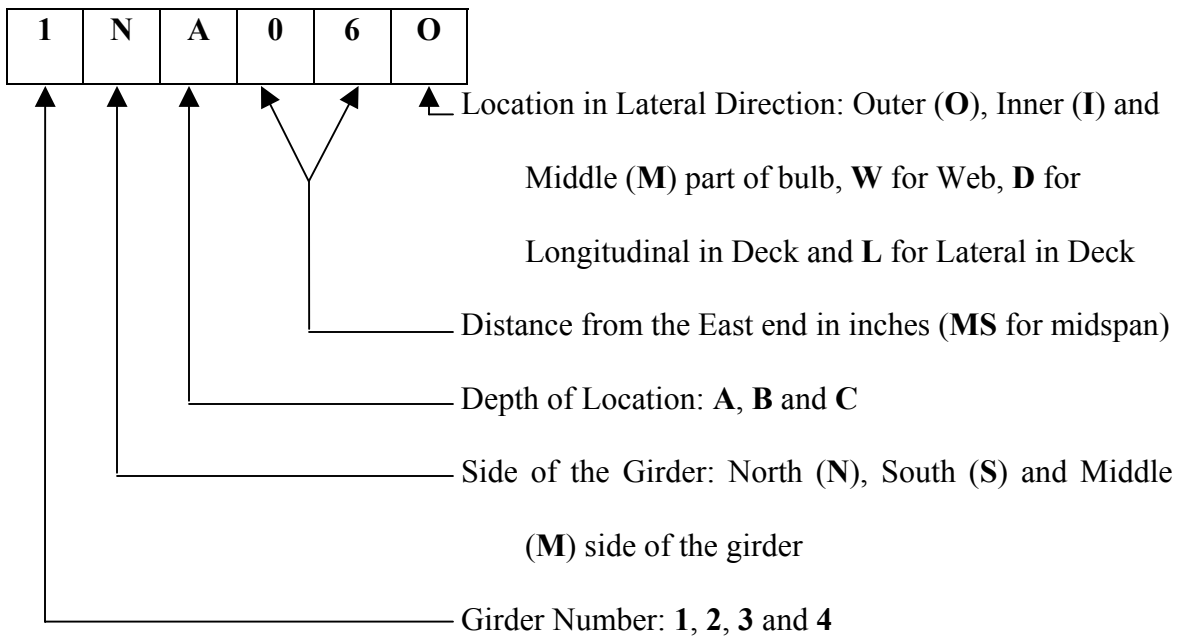


Figure 3.3 – Gage Identification Scheme

The characters in the identification scheme are more fully described by the following.

- **Girder Number:** There are four girders: 1, 2, 3 and 4. The first character in the gage name denotes the girder number.



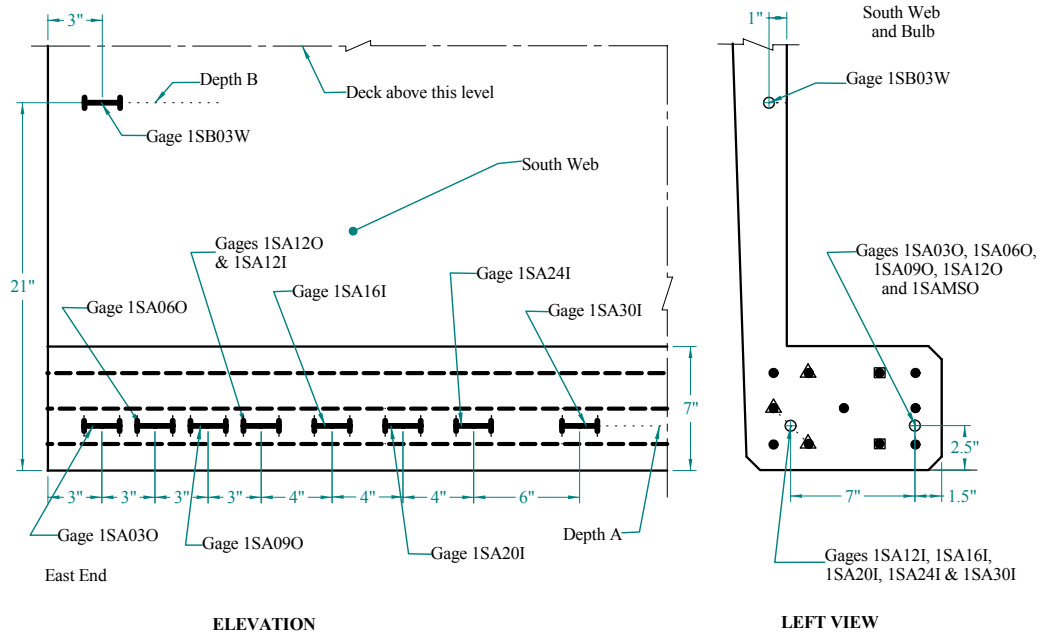
- **Girder Leg:** Each girder has a north (N) and a south (S) leg. The second character in the gage name denotes the girder leg. Note that the gages placed in the middle of the deck are denoted “M”.
- **Depth of Location:** There are three depths at which the gages have been located. They are Depth A – 2.5 in. up from the bottom in the bulb, Depth B – 12 in. down from the top of the deck in the web, Depth C – 2 in. down from the top of the deck in the deck. The third character in the gage name denotes the depth of location.
- **Distance from East End:** Gages were placed at various distances from the east end of the girders. These distances ranged from 2 in. to 30 in. The fourth and fifth characters in the gage name denote this distance in inches as a two-digit integer. Note that gages installed near the midspan of the girders are denoted “MS”.
- **Supplementary Location Identifier:** Among the gages installed in the bulbs, some of them are installed in the outer (O) part of the bulb (i.e., 1.5 in. from the outside edge), some in the inner (I) part (i.e., 8.5 in. from outside edge), and some in the middle (M) part (i.e., 3.5 in. from outside edge) of the bulb. The gages installed in the web are denoted by “W”. Gages placed laterally in the deck are denoted by “L”, while “D” denotes those cast longitudinally in the deck. .

An example of the gage identification scheme is as follows. A gage in Girder 1 in the North side at depth A, at 6 in. from the end and in the outer part of the bulb will be identified as 1NA06O. For gages in the inner or middle side of the bulb, an I or M will

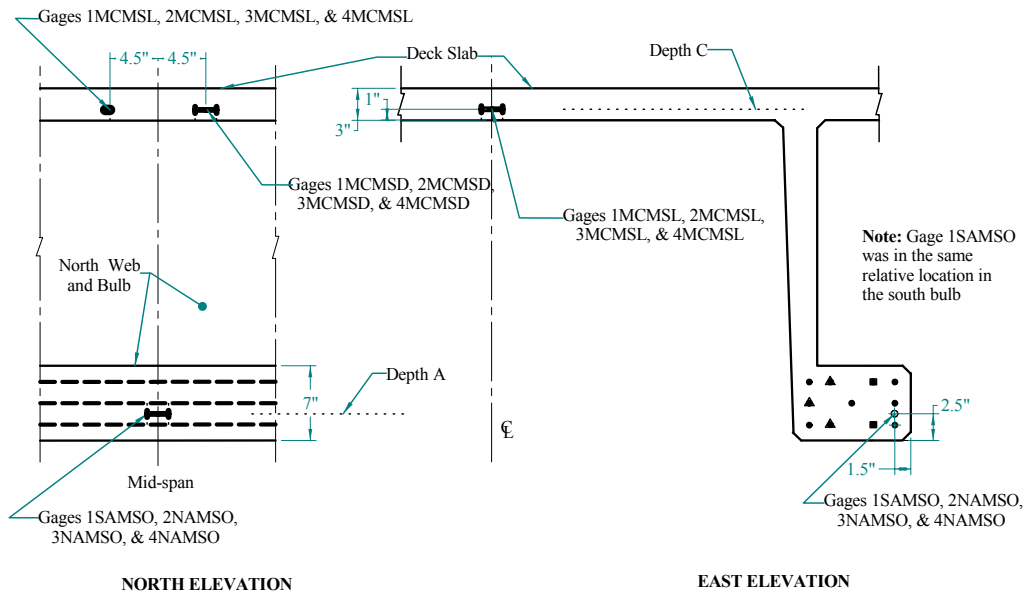
replace the O. A gage in Girder 4 in the South side at depth B, at 3 in. from the end and in the web will be identified as 4SB03W. Gages placed longitudinally in the midspan bulb are identified as 1SAMSO for girder 1, 2NAMSO for girder 2, etc., whereas gages placed longitudinally in the midspan deck are identified as 1MCMSD for girder 1, etc. Those placed laterally in the midspan deck are identified as 1MCMSL for girder 1, and so on.

### **Girder 1**

Thirteen vibration wire gages were cast into Girder 1. Nine of these were placed in the transfer region at the east end of the south bulb. From earlier estimates (*Steinberg E., Lubbers A., ISHPC 2003*), it was approximated that the transfer length should be in the range of 10 in. to 12 in. The three strands at the outer edge of the bulb are all fully bonded. Hence, as seen in Figure 3.4, the gages 1SA03O, 1SA06O, 1SA09O and 1SA12O provide the rate of transfer of the prestress of the non-debonded strands. The gages are installed in the concrete between the bottom two outer strands. The gages 1SA12I, 1SA16I, 1SA20I, 1SA24I and 1SA30I are located between strands that are debonded to 12 in. from the end of the girder. Ideally, the strain in the concrete near these gages should be a function of the strain due to the fully bonded strands and the strain due to the strands debonded to 12 in. and transferred thereafter. The purpose of these gages is to study the transfer behavior of the second set of strands, which are debonded to 12 in. The spacing between the gages has been increased and an extra gage (1SA12I) has been placed at 12 in. (effectively 0 in. of transfer) to record the strains in the concrete near the second set of strands due to the transfer of the fully bonded strands.



**INSTRUMENTATION PLAN FOR VIBRATING WIRE GAGES - GIRDER 1 AT SUPPORT**  
 Fig - 3.4



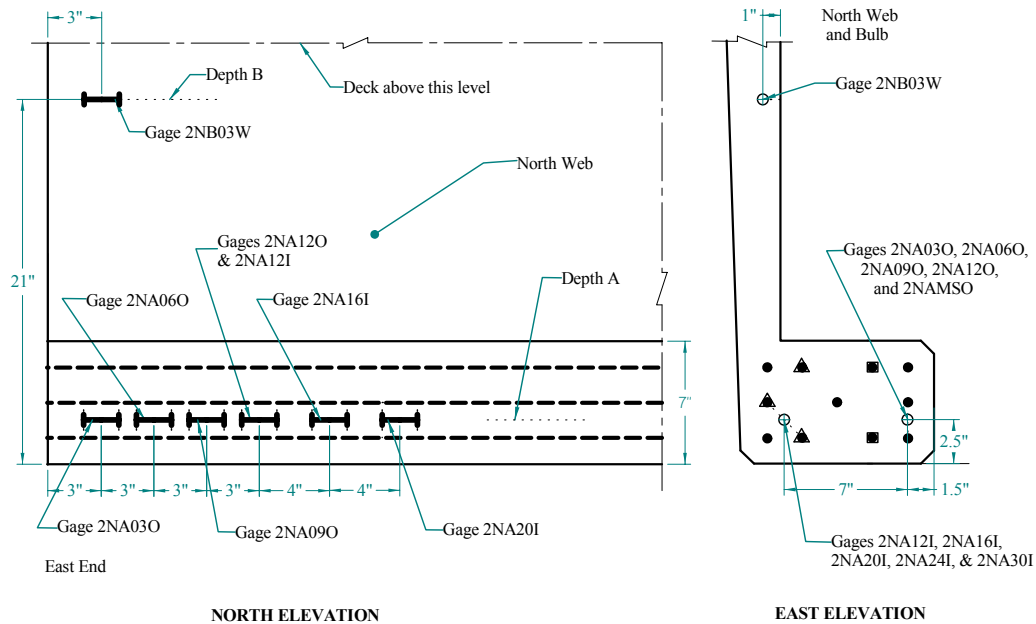
**INSTRUMENTATION PLAN FOR VIBRATING WIRE GAGES - GIRDER 1, 2, 3 & 4 AT MID-SPAN**  
 Fig - 3.5

The gage 1SA30I should provide an overall strain value after these two groups of strands have both transferred. Gage 1NB03W is cast into the web and is intended for a comparison between the strains at midspan and at the end at the level of the neutral axis. Three gages were cast into the girder near midspan. Gages 1SAMSO and 1MCMSD, as seen in figure 3.5, are primarily for the study of the flexural behavior of the girder at midspan. The 1SAMSO gage is in the same location in the girder cross-section as some of the transfer gages and thus can also be compared to those gages. The final gage in the first girder, 1MCMSL is for observation of the lateral strain behavior of the deck at the midspan.

Whittemore points were cast into this girder for additional data on midspan behavior, transfer, and shrinkage. These points were considered as an extra, inexpensive source of data. Whittemore points were installed in the underside of the thickened top flange and in the top of the bulb. The points were placed at a spacing of 1 in. up to 31 in. from the east end, then at 3 in. for another 12 in., and then at 6 in. to midspan. In all, the plan required placing 210 points in this girder, with 105 of them in the underside of the top flange and 105 in the top of the bulb. The points were placed along the south side of this girder.

## Girder 2

The instrumentation in the second girder was very similar to that in the first girder except for a few minor changes. The gages at 24 in. and 30 in. in the inner part of the bulb were not installed. As shown in figure 3.6, gages 2NB03W, 2NAMSO, 2MCMSD, and



INSTRUMENTATION PLAN FOR VIBRATING WIRE GAGES - GIRDER 2 AT SUPPORT  
Fig - 3.6

2MCMSL were kept at the same relative location, except that they were moved to the north bulb. Whittemore points were installed along the north side of this girder according to the same plan followed for the girder 1. Figure 3.7 (a) shows the Whittemore points for the underside of the overhang while figure 3.7 (b) shows the vibrating wire strain gages tied between the strands in the bulb.

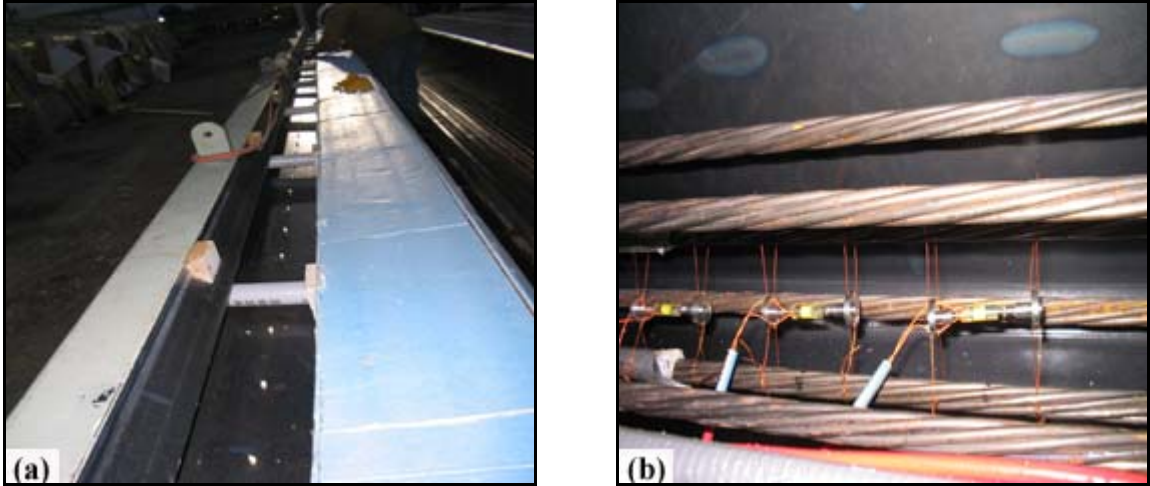
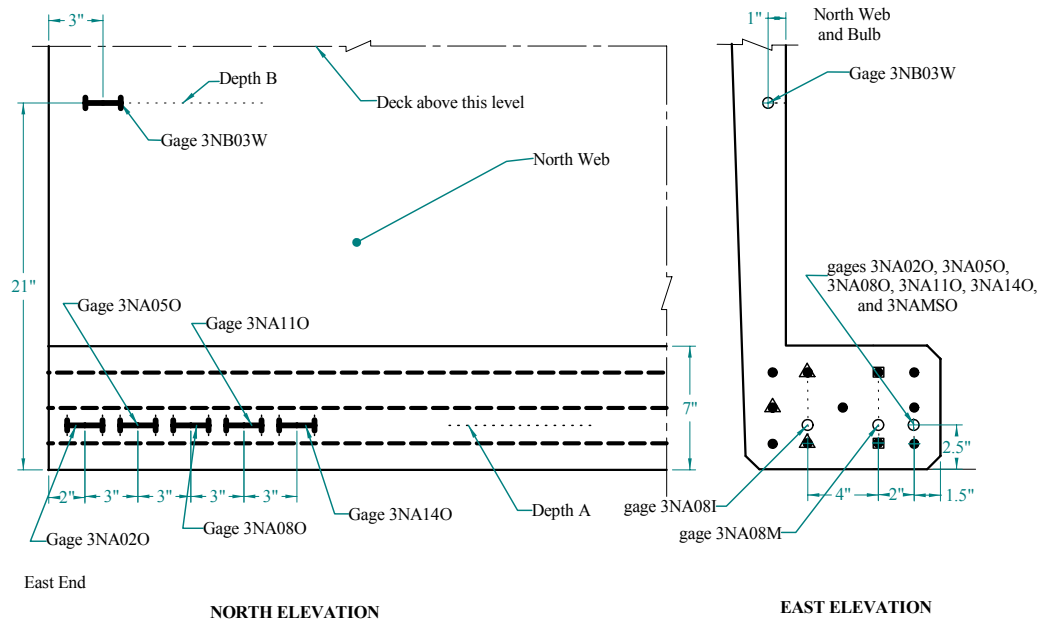


Figure 3.7 (a) Whittemore points and (b) Vibrating Wire Strain Gages

### **Girder 3**

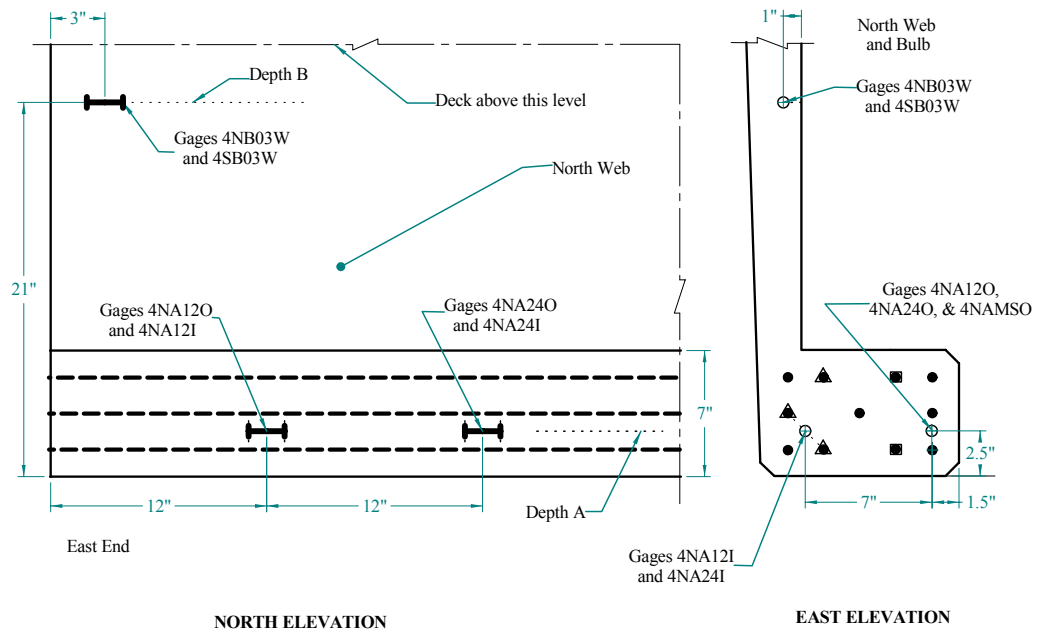
The analysis of the data from girders 1 and 2 suggested some modifications for girders 3 and 4. The outer bulb transfer curve plotted for the first and second girders had transfer strain values at 3, 6, 9 and 12 inches. Hence, in order to more accurately determine the strand transfer behavior, gages 3NA02O, 3NA05O, 3NA08O, 3NA11O, and 3NA14 were installed as shown in Figure 3.8. Also from the data recorded for girders 1 and 2, it was observed that there was a lag between the strains in the inner and outer bulb at the same distance from the end of the girder. This was particularly evident between gages 1NA12O and 1NA12I or 2NA12O and 2NA12I. To better quantify the lag occurring laterally in the bulb, two gages, 3NA08M and 3NA08I, were installed along with gage 3NA08O. The midspan and web gages (3NB03W, 3NAMSO, 3MCMSD, and 3MCMSL) were again installed in this girder and are shown in figure 3.8. Whittemore points were not installed in this girder.



INSTRUMENTATION PLAN FOR VIBRATING WIRE GAGES - GIRDER 3 AT SUPPORT  
Fig - 3.8

## Girder 4

As stated above, gages installed in girders 3 and 4 were to acquire data that was not obtained in the first two girders. Figure 3.9 shows that, in girder 4, the gages were installed in order to obtain transfer data for the strands debonded to 12 in., midspan behavior, and shrinkage. Gages 4NA12O, 4NA24O, 4NA12I, and 4NA24I were installed to capture the strain in the fully bonded strands and the strands debonded to 12 in. Gages 4NAMS0, 4MCMSD, and 4MCMSL were installed as before. In the third girder, the UHPC premix used was from different production runs and hence the girder showed different shrinkage rates in the two legs of the girder. There was a possibility of the same behavior occurring in the fourth girder so an extra gage, 4SB03W, was placed in the south web. Thus in this girder there were two shrinkage gages, one each in the north and



INSTRUMENTATION PLAN FOR VIBRATING WIRE GAGES - GIRDER 4 AT SUPPORT  
Fig - 3.9

south webs of the girder. As in the third girder, Whittemore points were not installed.



## **Chapter 4 - Fabrication**

### **4.1 Introduction:**

This chapter covers the preparatory actions and the physical procedures undertaken to cast the four optimized girders. This includes the casting of trial girder sections and the casting procedure. Also included are the curing methods utilized and the procedure followed to release the prestressing strands.

### **4.2 Trial Sections:**

Test casts were done before the actual girders were cast so as to refine the mixing and casting procedures. In all, five test pieces of the same cross section as that of the actual girder were cast. Each of the first four test pieces had certain issues while the fifth was successful and allowed the casting to progress to the full girders.

A summary of the trial girder sections follows. The first trial girder section was 10 ft. in length. The placing of the UHPC was completed without the aid of a trough. The UHPC started gaining strength earlier than expected and later showed shrinkage cracks. Most of the deck cracks were across the deck (i.e., from one web toward the other) and some of these cracks were large (approximately an 0.05 in. opening) indicating that there may have been a lack of fibers across some cracks in the deck. There was also one vertical crack in each web. The second trial girder section was 8 ft. long and cast without a trough. It also showed cracks transverse to the length of the girder piece as were observed in the first girder; however these were tighter. This girder also had fiber

alignment issues. The third trial girder section was 7 ft. in length. It was cast under direct mid-day sunlight without a trough, and insufficient material led to a slow rate of placement of the deck. This girder showed deck cracks both along the length of the girder as well as circumferential cracks around the pour location in the center of the deck. The casting problems led to a new casting procedure for the next cast. Also, measures to keep the formwork and the girder cooler and hence retarding the setting time were considered. The fourth trial girder section was also 7 ft. in length. This cast included placement of the deck via a trough and sufficient material to rapidly fill the deck. The forms were released when the UHPC started showing a rise in temperature; however, the UHPC had not yet gained sufficient strength. The section cracked in flexure above the web and at the center of the deck. The fifth and final trial girder section was again 7 ft. long with its deck cast from a trough. The section was monitored for rise in temperature and for penetration resistance to determine the formwork release time. This trial girder section did not show any significant cracks.

#### **4.3 Formwork Erection and Instrumentation:**

The formwork for the cross-section of this girder exhibits considerable restraint on the girder as the concrete begins to set and shrink. But the early-age shrinkage behavior of UHPC is such that it causes the UHPC matrix to crack if it is restrained beyond the initiation on setting. Thus, a specially constructed steel formwork, which allowed the girder to shrink laterally after it had achieved sufficient strength to support itself, was used for casting all four girders. The formwork consisted of three parts, the inside form which supported the deck and the inside of the webs, and the two outside forms that

supported the overhang and the outsides of the webs. The inside form consisted of a stationary center post and articulating arms supported from below by turnbuckles. The blackout on the underside of each overhang was formed from foam-covered plywood boxes. The east and the west end of the forms had blockouts with coil inserts at the deck level to provide a shear connection between the girder and the diaphragms. Blockouts were also placed at fixed intervals along the north and south edges of the deck to provide for the bolted and welded connections. Finally, two coil bolt inserts were specified for each lifting point. Figures 4.1(a) and 4.1(b) show the formwork for the girders.

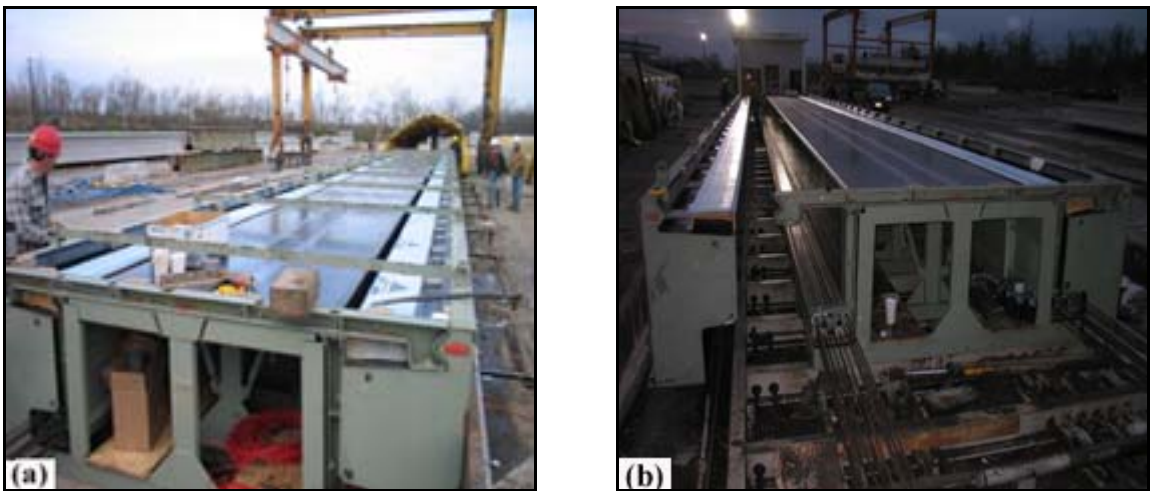


Figure 4.1 – Girder Formwork

The formwork erection procedure started with the assembly of the inner formwork. Next, the strands were installed in the formwork and stressed. The vibrating wire gages and Whittemore points were then attached to the strands and formwork. The outside formwork was then installed, the formwork was sealed, and the blockouts and lifting inserts were installed.

#### **4.4 Prestressing Scheme:**

Low relaxation strands, 270-ksi 0.5 in. diameter prestressing strands, were installed in the girders. They were pulled based on force and elongation calculations with 19” and 21” as the specified minimum and maximum elongation of the strands. All strands were pulled to 29.2 kips of force.

#### **4.5 Mixing:**

**Mix Design:** Table 4.1 provides the mix design in terms of manufacturer-supplied premix, water, superplasticizer, and fibers. See Table 2.1 in Chapter 2 for a description of the premix.

Table 4.1 UHPC Mix Design

<b>Girder No.</b>	<b>Batch No.</b>	<b>Premix (lbs.)</b>	<b>Superplasticizer (lbs.)</b>	<b>Water (lbs.)</b>	<b>Steel Fiber (Box + lbs.)</b>
<b>Girder 1</b>	Batch 1	14000	193	100	15B + 11
	Batch 2	14000	193	101	15B + 11
	Batch 3	14000	193	102	15B + 11
	Batch 4	12000	165	88	15B + 11
<b>Girder 2</b>	Batch 1	14000	193	100	15B + 11
	Batch 2	14000	193	100	15B + 11
	Batch 3	14000	193	100	15B + 11
	Batch 4	12000	165	89	13B
<b>Girder 3</b>	Batch 1	14000	193	102	15B + 11
	Batch 2	14000	193	102	15B + 11
	Batch 3	14000	193	104	15B + 11
	Batch 4	11870	163	88	13B
<b>Girder 4</b>	Batch 1	14000	193	102	15B + 11
	Batch 2	14000	193	103	15B + 11
	Batch 3	14000	193	104	15B + 11
	Batch 4	11965	163	90	13B

Each casting included one girder requiring 11 yd<sup>3</sup> of material and various other small pieces (i.e., diaphragms, test slabs, cylinders, etc.) totaling approximately 1 yd<sup>3</sup>. A total of 14.6 yd<sup>3</sup> was mixed for each casting. This total volume of material was mixed in four approximately equal batches. The premix was scaled into the mixer from an emptied cement silo in increments of 4000 lbs or less. Once the premix was in the mixer it was dry-mixed for about 5 minutes. Next the water was added along with half of the superplasticizer (Glenium 3000 NS) and the addition took about 2 minutes. Mixing was done for 5-6 minutes until the concrete began to flow. The rest of the superplasticizer was then added. The fibers were added two minutes after the addition of the superplasticizer. The fiber addition (around 15 boxes) took approximately 6 minutes. The concrete was then slowly mixed for two minutes while an ASTM C230 shock table test was completed. The results of these tests are shown in Table 4.2. The concrete was then placed into a ready mix truck.

Table 4.2 ASTM C230 Shock Table Test Results

	<b>Static Flow (mm)</b>	<b>Dynamic Flow (mm)</b>
<b>Girder 1</b>	195 – 200	235
<b>Girder 2</b>	200 – 210	220 – 240
<b>Girder 3</b>	200 – 205	230 – 235
<b>Girder 4</b>	200	230

Figure 4.2(a) shows the mixer used for the mixing of UHPC while Figure 4.2(b) shows the UHPC while it is being mixed.

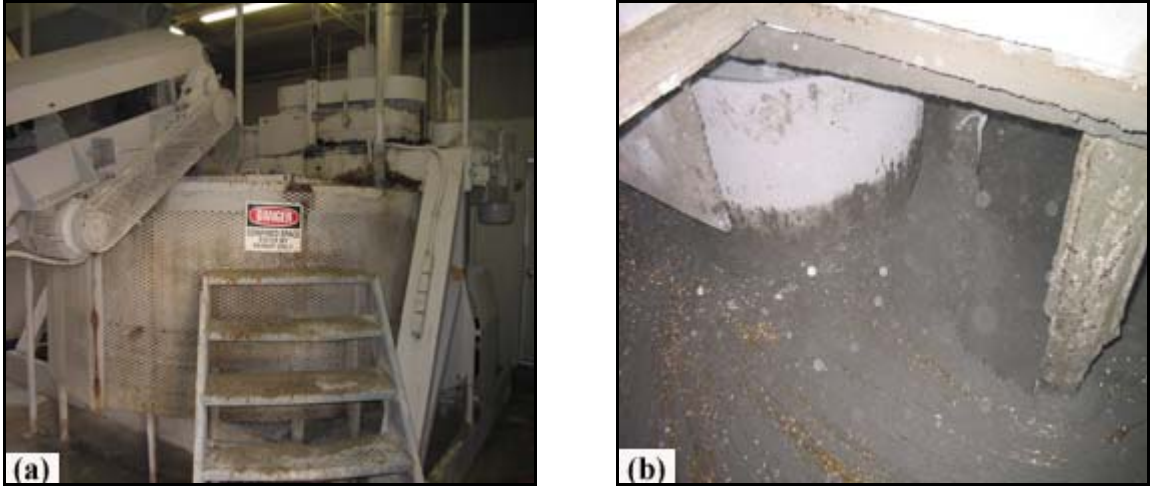


Figure 4.2 (a) Mixer and (b) UHPC being Mixed

Temperatures were recorded at different stages during the mixing. These environmental and material temperature values are shown in Table 4.3.

Table 4.3 UHPC Mixing Temperature

	Temperature Range in degrees Celsius			
	<b>Girder 1</b>	<b>Girder 2</b>	<b>Girder 3</b>	<b>Girder 4</b>
<b>Ambient Temp</b>	16.0 – 20.0	12.0 – 13.0	2.0 – 4.0	-6.0 - -4.0
<b>Premix Introduction</b>	17.3 – 18.6	14.8 – 16.5	12.0 – 13.0	17.5 – 18.5
<b>Water and ½ Super.</b>	17.3 – 21.1	16.4 – 17.0	12.0 – 14.0	16.5 – 17.5
<b>Rest of the Super.</b>	21.2 – 24.2	19.4 – 21.8	14.0 – 16.0	18.5 – 19.5
<b>Fiber Introduction</b>	22.3 – 25.0	19.1 – 22.6	14.0 – 16.5	17.0 – 18.5
<b>Final Mix- Discharge</b>	22.7 – 25.5	20.6 – 22.6	16.0 – 22.7	17.5 – 18.5

#### **4.6 Placing:**

The concrete was transported to the formwork in two ready-mix trucks. The trucks, one on each side of the form, started at one end of the girder and filled the bulbs traveling

toward the other end. The trucks moved forward as the webs were filled up to one-third height. Once the first pass was completed, the trucks began to discharge into a trough that spanned across the deck. The trough had an opening of  $\frac{3}{4}$  in. that ran across the girder and this allowed the concrete to be placed into the form evenly across the girder width. The trough was moved forward along with the trucks as the deck was filled. Manual agitation was used to mix the two layers of concrete in each web. A water mist was also used to ensure that the first lift surface did not dehydrate prior to placement of the second lift. Figure 4.3(a) shows the concrete being placed in the web formwork while figure 4.3(b) shows the concrete flowing into the web and around the instrumentation.

Plastic sheets were used to cover the deck as soon as it was cast and tents were placed over the girders to block the sunlight and dehydration.



Figure 4.3 Placing UHPC

#### **4.7 Material Characterization Test Samples:**

Concrete samples were collected from each truck for material testing. These samples included 3 in. diameter by 6 in. long cylinders, 4 in. diameter by 8 in. long cylinders, 2 in. by 2 in. prisms, and mortar briquettes. The 3 in. by 6 in. cylinders were used on site to determine strength levels of the concrete.

#### **4.8 Release of Formwork and Prestressing:**

Each girder was closely monitored so that both the inner and outer forms could be released as soon as the girder had enough strength to support itself. This was important because, if the form was not released, the concrete could go, in a short time frame, from being plastic to having longitudinal shrinkage cracking. In practical terms, monitoring the strength and shrinkage of the UHPC for determination of the release time for the girders requires three things: 1) uniform environmental conditions throughout the deck and any test pieces, 2) unrestrained shrinkage data for UHPC that has been exposed to identical conditions as the restrained UHPC in the deck, and 3) differentiation between thermally induced strains and shrinkage strains at various stages of concrete plasticity. Given the outdoor fabrication environment and the thermal behavior of various size masses of setting concrete, monitoring of temperature and shrinkage behavior was not sufficient to determine the formwork release time. Hence, penetration resistance of the deck concrete was used as a second method for determining both the degree and the uniformity of setting throughout the deck. Penetration of less than 1/8 in. with a manually forced 1/16 in. diameter flat-head penetrometer tended to indicate sufficient strength. The UHPC did not begin to set until approximately 24 hours after casting. The



penetration resistance as well as the temperature and shrinkage recorded by the gages showed a marked increase as the concrete began to set. The form elements providing restraint were gradually released as the setting progressed. First, the screws holding the Whittemore points and the chairs for the vibrating wire gages were released. Generally, the end and overhang blockouts were next, followed by the turnbuckles and inner forms. Lastly, the top and bottom clamps and outer forms were released. Figure 4.4(a) shows the inner forms after they were released and figure 4.4(b) shows the prestressing strands being cut.



Figure 4.4 (a) Inner Forms Released and (b) Prestressing Strands being Cut.

The girders were designed to be prestressed once companion cylinders showed strengths of over 10 ksi. However, if the girders were stressed too early then tensile stresses in the deck caused by negative flexure could result in objectionably large cracks that extend down to near the bottom of the web. After releasing the formwork and ascertaining that the girder had gained adequate strength, the prestressing was applied to the girders.

Standard techniques were used for stressing the girders. Each of the strands in both the bulbs was cut simultaneously at each end. The strands were cut symmetrically starting with the strands at the top of the web (for girders 3 and 4 only), then the draped strands (for girder 4 only, after cutting the hold-downs) and then the strands in the bulbs starting with the top inner strand on the south bulb, then the top inner strand on the north bulb, etc., through the bottom outer strand on the north bulb.

#### **4.9 Lifting and Blocking of Girders:**

After the strands in the girder bulb were cut, the girder was lifted out of the forms by means of the coil bolt lifting inserts with a mobile crane so that the casting bed would be free for the next girder. It was then blocked approximately 12 in. from each end. This blocking location allowed for the construction of the diaphragm formwork. Figure 4.5(a) shows the girders being lifted and figure 4.5(b) shows the girders after they are blocked.



Figure 4.5 (a) Girder being Lifted and (b) Girder after it was Blocked.

#### **4.10 Casting of Diaphragms:**

Diaphragms were cast onto each end of each girder through a secondary pour. In general, each girder casting included the casting of the previous girder's diaphragms. If environmental conditions warranted, the girders were draped in tarps and a portable propane heater was placed under them. This was to ensure that the diaphragms did not freeze before setting. Figure 4.6(a) shows the formwork and casting of a diaphragm while figure 4.6(b) shows the girder after the diaphragm was cast.

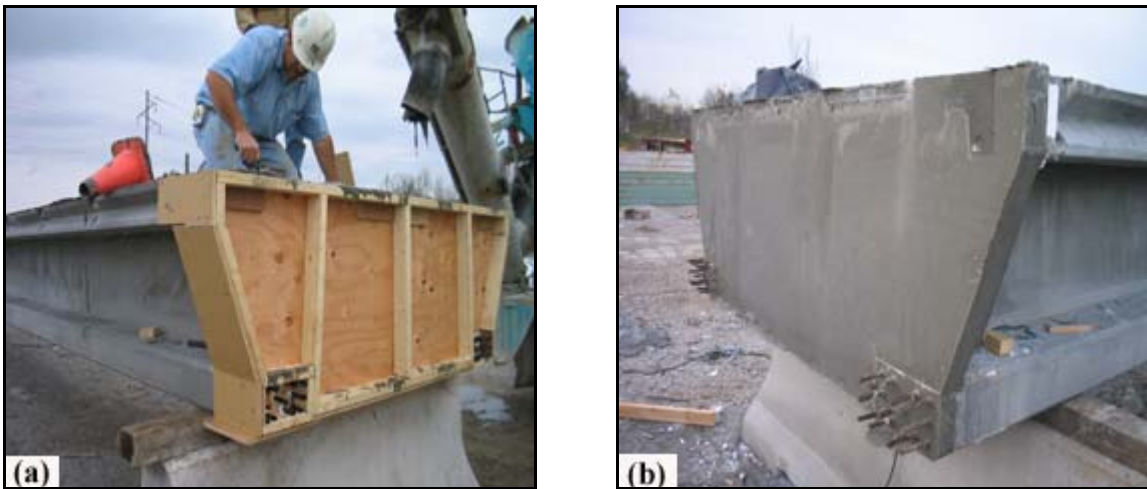


Figure 4.6 (a) Diaphragm being Cast and (b) Girder after Diaphragm Cast.

#### **4.11 Steam Curing:**

The UHPC suppliers' recommendations include steam curing cast pieces for at least 48 hours at 90 degrees Celsius and 95% humidity. After stressing, the girders were steam cured as recommended for approximately 48 to 72 hours with at least 24 hours of ramp up and ramp down time. The steaming temperature rise and drop were controlled so that

the UHPC would not be shocked and damaged. The temperature of each girder was monitored using a temperature probe.

#### **4.12 Special Precautions and Monitoring of Girders:**

A number of special precautions were followed for the fabrication of these girders.

- Special care was taken to ensure that the instrumentation, particularly the vibrating wire gages, were not disturbed or damaged during operations such as formwork installation, casting, etc.
- If multiple ages of premix material were to be used in one casting then it was specified that all batches had an equal amount of the older and the newer premixes.
- Both fans and a hot water heat system were used to maintain the ambient temperature surrounding the setting concrete. Temperatures between 60°F and 80°F were considered acceptable. Also, the tents were closed to limit external weather (i.e., wind, sun, freezing temperatures, etc.) ingress and to help maintain a uniform environment around the setting concrete.
- After casting, the girders were monitored at regular intervals. The monitoring included reading the strain gages and checking the penetration resistance of the UHPC.
- The restraint to thermal contraction or expansion caused by the strands in the girder was always kept in mind while increasing or decreasing the girder temperature. In effect, the rate of increase or decrease of the temperature in the test was kept at a moderate level until the strands were cut.

## Chapter 5 – Early Age Behavior

### 5.1 Shrinkage Behavior

#### 5.1.1 Introduction:

This chapter covers the concrete shrinkage behavior observed during the casting and curing of the girders. The chapter starts by stating the significance of the shrinkage analysis of the UHPC girders. This is followed by a section on the casting processes and the artificial and natural conditions to which the girders were exposed that might have had a bearing on the shrinkage. The shrinkage behavior of the girders is then discussed. Basically, the shrinkage behavior is divided into two parts, early age shrinkage (i.e., shrinkage before the application of prestress) and steam treatment shrinkage.

#### 5.1.2 Significance:

Results from unrestrained shrinkage tests done in the laboratory for air cured, steam treated, and delayed steam treated UHPC specimens are available. However, actual behaviors observed in casting full scale prestressed concrete girders could be very different. The observed strain changes of UHPC in the girder could be affected by the changes in ambient temperature, steam temperature, formwork restraint, etc. Therefore, the inability to completely control the parameters as well as the variations in the conditions to which various parts of the UHPC girder are exposed makes this study of particular interest and varied from the laboratory shrinkage tests.

### **5.1.3 Casting, Temperature Control, and Stripping of Forms:**

As discussed in the previous chapter, trial girder sections were cast before casting the actual girders. This was done to get an idea of the UHPC behavior when cast as a large, complex element. The problems encountered and addressed included fiber alignment, placing method, and sequence of form release so as to prevent restrained shrinkage cracking.

### **5.1.4 Early Age Shrinkage Behavior:**

#### **Girder 1**

Figure 5.1 shows the shrinkage behavior and the temperature variations of concrete at different locations in Girder 1 as well as the temperature outside the girder from the cast time to the cutting of strands. The first 15 hours after the girder is cast show reduction in the temperature both inside and outside of the girder; however, it is not accompanied by any volumetric changes in the girder. The air temperature inside the tent is slightly higher than that shown by the gages inside the girder. By 20 hours after casting, the tent temperatures are showing a marked increase with the concrete seeming to exhibit volumetric expansion. The strains tend to increase at most locations and many of the gages, particularly the transfer gages, shift from being under compression or no strain to going into tension with 1SA03O showing the greatest variation. The shrinkage activity shows reduction with the distance inwards from the end of the girder, whereas the gages at midspan (i.e., 1SAMSO, 1MCMSD and 1MCMSL) show very little strain change. At

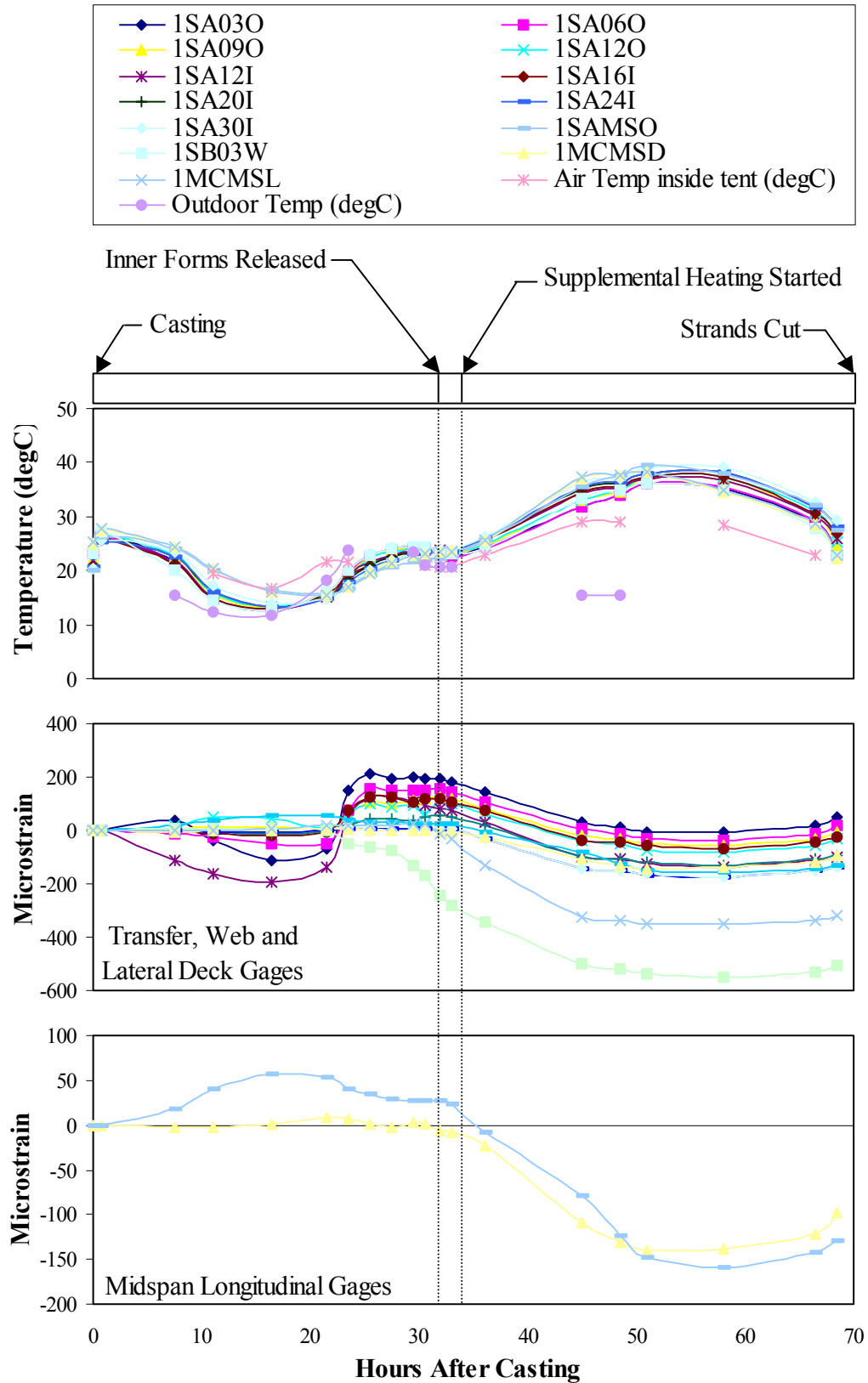


Figure 5.1 - Early Shrinkage Before Strands Cut, Girder 1

approximately 24 hours the welded connections and the overhang blockouts are released. The outdoor temperature rise slows down soon and within a couple of hours the temperature starts decreasing. The temperature inside the tent and the temperatures in the gages also show the same pattern but the temperatures in the gages do not decrease as sharply as the outdoor temperature. Lateral shrinkage cracks are observed in the surface of the deck at about 25 hours after casting. As soon as the cracks are observed, it can be seen that the temperature inside the girder also tends to fall down and the tensile strains suddenly relax and all the gages start showing either compressive strains or stabilizing. After 30 hours the end blockouts and the inner forms are released, but it doesn't seem to have much effect on shrinkage except that gage 1MCMSL, which after the release on the inner form is in an unrestrained location, shows faster shrinkage rate. Around this time the temperature in the girder starts reducing slightly until 34 hours, when high humidity supplementary heating is started. This heating expedites the shrinkage, with 11 microstrain/hr occurring in most transfer gages for the next 12 hours. After 45 hours the shrinkage behavior begins to subside and the volumetric changes become more closely tied to the internal temperature changes. At 46 hours the top and bottom clamps are removed and the side forms are broken loose.

Figure 5.1 shows that, apart from the first 15 hours, all gages except the lateral midspan deck and the longitudinal web gages are showing similar shrinkage behavior. These two gages are subject to more or less the same conditions as the other gages aside from the level of restraint provided by the formwork and strands. Gage 1MCMSL is the only lateral gage in the girder, and as such it is in a position that is either fully restrained or



fully unrestrained depending on the formwork. Gage 1MCMSL clearly shows the effect of this restraint as it exhibits approximately 25 microstrain/hour of shrinkage after the inner form is released while the always partially restrained gage 1MCMSD exhibits 7 microstrain/hour during the same timeframe. Gage 1SB03W is also restrained differently by being in the web very close to the end of the girder. Figure 5.1 clearly shows how this relatively unrestrained location can begin to shrink approximately 5 hours before the remainder of the gages show any shrinkage. The strain in the longitudinal midspan gages 1MCMSD and 1SAMSO are observed in the bottom plot in Figure 5.1. It can be seen that gage 1SAMSO shows larger variations in volumetric change as compared to the gage 1MCMSD. The gage 1SAMSO is embedded in the south bulb at midspan and is at the bottom and hence closer to the heating conduits. Thus this part of the girder gets more concentrated heating and shows larger shrinkage as compared to the deck gage.

### ***Girder 2***

Figure 5.2 shows the shrinkage behavior and the temperature variations of concrete at different locations in Girder 2 as well as the temperature outside the girder from the cast time to the cutting of strands. There is a slight reduction in the concrete temperature in the first 10 hours after casting, after which the temperature remains almost constant for another 20 hours and the surrounding temperature (i.e., the temperature in the tent) also varies little and is the same as that observed inside the girder. By observing the behavior of the gages it can be seen that the concrete does not show any volumetric changes in the first 32 hours except at gage 2NB03W in the web near the end of the girder. The deck end and the overhang blockouts are released at around 30 hours. The temperature inside

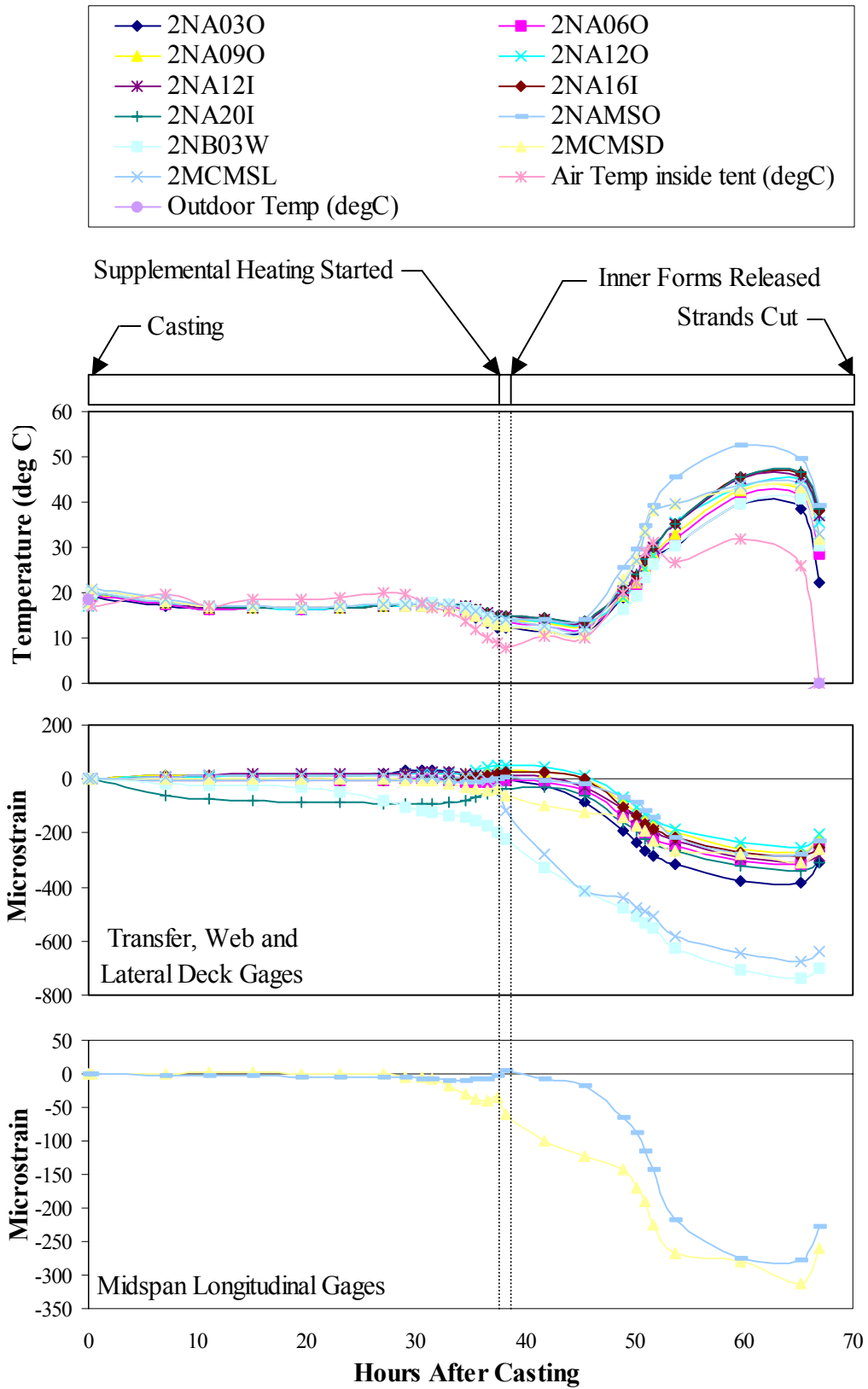


Figure 5.2 - Early Shrinkage Before Strands Cut, Girder 2

the tent as well as inside the girder starts reducing after 30 hours. The concrete shows a slight expansion in most locations on the girder at this stage as is also seen in Girder 1. At about 38 hours the inner form is released and high humidity supplemental heating is started.

As was observed in Girder 1, the lateral gage in the deck shows immediate shrinkage as the restraint is removed. In fact, it shrinks at a rapid enough pace to quickly catch up to the web shrinkage gage, which had been showing shrinkage for the previous 15 hours. Gage 2NB03W exhibited 12 microstrain/hour shrinkage for 15 hours until the inner form was released, then it exhibited 26 microstrain/hour for an additional 15 hours. Comparatively, the lateral deck gage 2MCMSL exhibited 50 microstrain/hour for 8 hours before slowing to 20 microstrain/hour for another 8 hours. Figure 5.2 also shows that the transfer regime exhibited very little shrinkage until 5 hours after the form release when the temperature in the girder began to increase. Finally, note how the midspan bulb gage exhibits a significantly delayed shrinkage response as compared to the comparatively less restrained longitudinal midspan deck gage.

At 51 hours, the top and bottom clamps are removed and the side forms are broken loose. The supplemental high humidity heating is also reduced at the time. From here on, the temperature and strain plots of Figure 5.2 are almost mirror images of each other.

### ***Girder 3***

Girder 3 exhibits slightly different shrinkage behavior as compared to the first two girders. Their behaviors are more difficult to discern due to variations in the surrounding air temperature in the tent. Figure 5.3 shows the shrinkage behavior and temperature of concrete at different locations in Girder 3 from the cast time to the cutting of strands as well as the temperature variations in the tent and the ambient temperature. It can be seen that the concrete does not undergo much volumetric change in the first 20 hours. The outdoor temperature in this girder stays at around 0°C throughout and goes below zero during the early morning hours. The temperature inside the tent is kept much higher using low temperature steam right from the time the girder is cast. It can be seen in the temperature plots for Figures 5.1, 5.2 and 5.3 that the gage in the bulb at mid-span shows the highest temperature when the girders are subject to high humidity supplemental heating. This is due to a steam vent near the center of the girder. In Figure 5.3, it can be seen that the concrete near gage 3NAMS0 shows shrinkage much earlier than the other gages and the temperature plot also highlights the greater temperature it reaches due to continuous steam curing. After 20 hours the increase in the concrete temperature accelerates and the shrinkage activity also begins. The concrete reaches the maximum temperature of about 40°C (gage 3NAMS0 reaches 50°C) at 40 hours after casting. It can be seen that the air temperature in the tent is much lower at about 26°C. The welded connections, overhang blockouts, and end blockouts are released at around 40 hours and the supplemental heating is decreased at the same time.

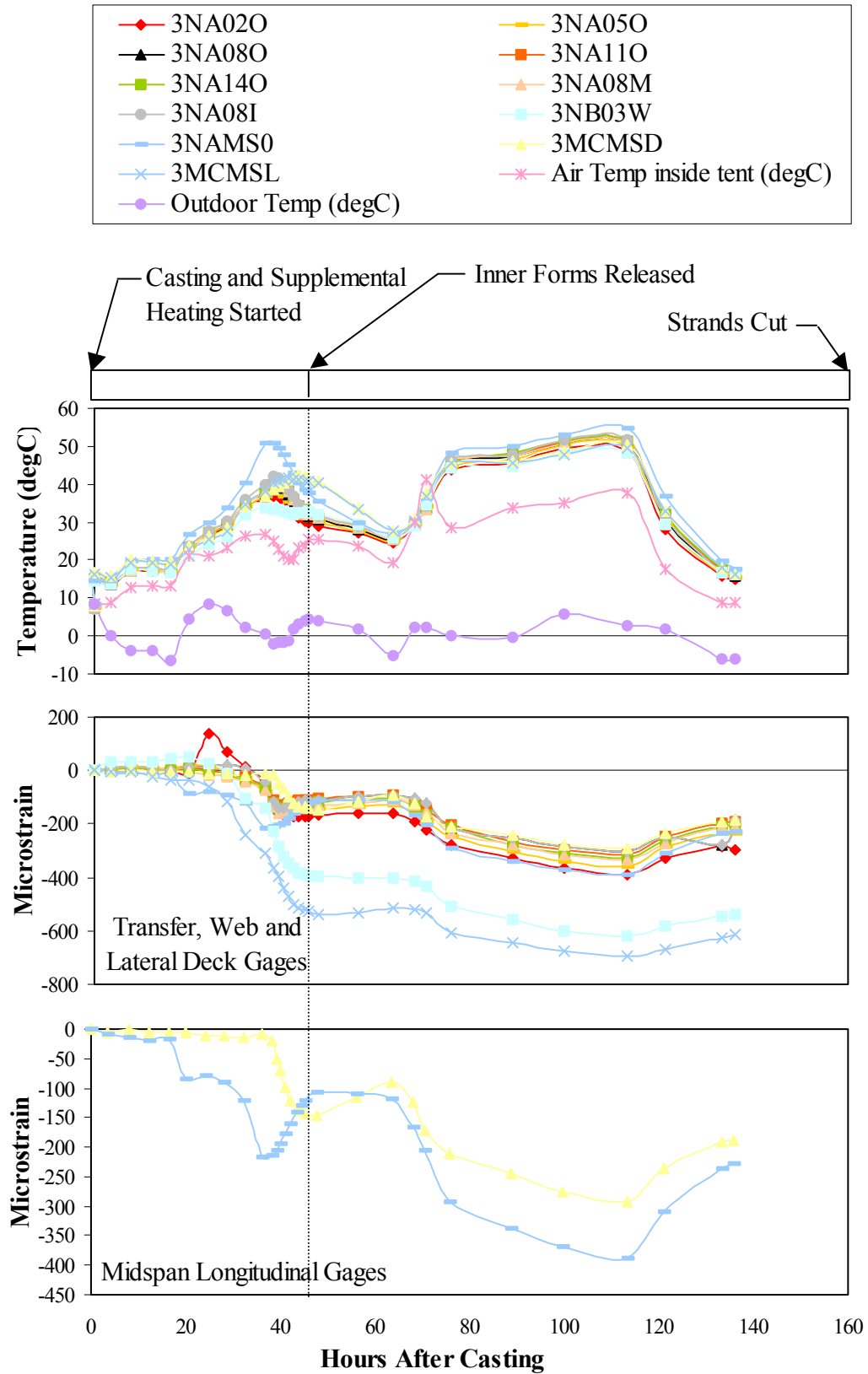


Figure 5.3 - Early Shrinkage Before Strands Cut, Girder 3

The inner form is released at 45 hours; however, this does not seem to have a significant effect on the shrinkage behavior. The transfer region gages started to show shrinkage at 24 hours and the web gage showed shrinkage starting at 20 hours. The inner form was not released until 45 hours because penetration resistance testing indicated that the deck was not sufficiently strong. The primary reason for the differences in behavior compared to the earlier girders is related to the premix. This girder contained two different ages of premix, which were not evenly distributed between the two ready-mix placing trucks. This resulted in a faster setting mix being placed on the north side of the girder. Thus, the north side (where all the gages were located) began to shrink earlier while a significant part of the deck was showing no penetration resistance due to its slower setting. This allowed for virtually no lateral restraint in the deck and thus this shrinkage could occur unimpaired regardless of the release of the inner form. At around 64 hours the steaming temperature is increased and the concrete also shows rapid volume change (12 microstrain/hr). This girder has two shrinkage slopes that are linked by a zone during which slight expansion takes place. The zone of slight expansion coincides with the period of hiatus in the steaming being carried out on the girder. The steaming is again stopped at 70 hours and the temperature in the tent drops rapidly before the steaming is again started at 75 hours at a gradual rate. The concrete temperature continues to rise until 75 hours even though the steaming has been stopped and then the gain in temperature slows down to the rate of gradual steaming being carried out after 75 hours. The steaming is continued until 115 hours from casting and in this period the girder strains at approximately 3 microstrain/hr. The steaming is stopped at about 115 hours and the temperature in the girder and in the tent drops down rapidly due to the cold

outdoor conditions. This is accompanied by tensile strains in the girder before the strands are cut.

As observed in all the girders, gages 3NB03W and 3MCMSL show much higher shrinkage rate (27 microstrain/hr) during initial shrinkage than the other gages (16 microstrain/hr), whereas the subsequent expansion and then shrinkage rates are almost equal.

#### ***Girder 4***

Figure 5.4 shows the shrinkage behavior of concrete and temperature variations at different locations in Girder 4 as well as the ambient temperatures outside and inside the tent from the cast time to the cutting of strands. This girder has also been cast in cold conditions as can be seen by the plot for outdoor temperature in Figure 5.4 and hence it has been subject to supplemental heating right from the time it was cast. It can be seen that the heating is continued for 30 hours and leads to an increase in the temperature of the girder concrete and that in the tent. Girder 4 shows slightly different behavior than the earlier girders. As seen in Figure 5.4, all the gages show almost the same small amount of strain in the first 15 hours, after which the gages in the bulb remain relatively constant while the gages in the webs and deck begin to show some shrinkage. At 30 hours the temperature inside the tent is reduced. At approximately the same time the gages outside the bulbs begin to show enhanced shrinkage. At 35 hours the inner form is released. In this girder, the form release had very little effect on the shrinkage behavior. It is likely that this again relates to the mix of different age premixes that were used in this girder.

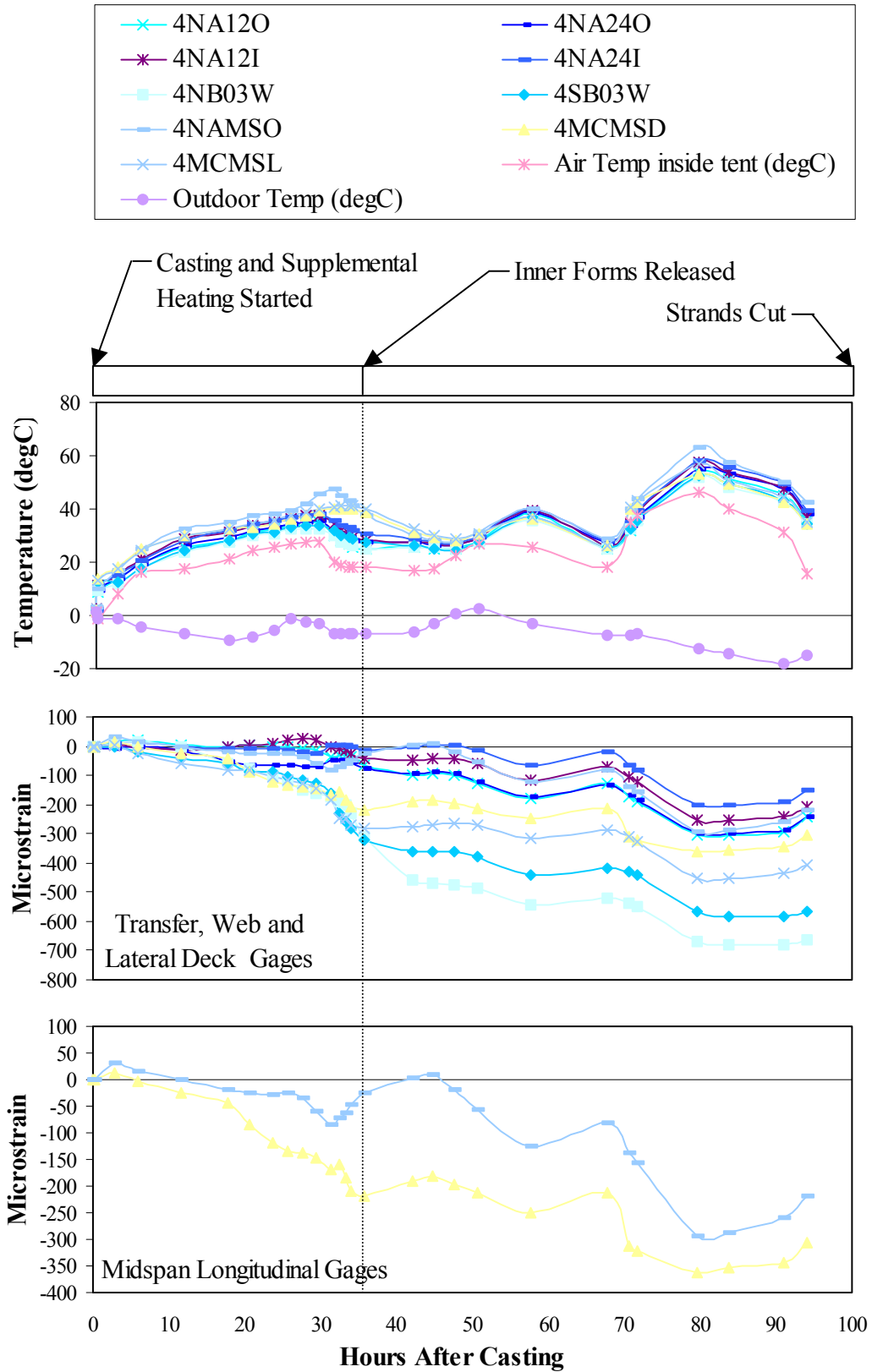


Figure 5.4 - Early Shrinkage Before Strands Cut, Girder 4



For this casting, the different premixes were equally blended into each batch so the cast material was consistent. However, it seems likely that the differing set times of the premixes could have affected the setting enough to relieve some restraint and allow for the shrinkage before the inner form release. After 45 hours the outdoor temperature as well as the temperature inside the tent increase and the girder, after some time, also starts heating up. The concrete in all parts of the girder starts showing shrinkage at the rate of about 8 microstrain/hr for 10 hours. As in previous girders, the web gages show more shrinkage than the other gages in the earlier stages. Gage 4SB03W, installed in the south web to monitor the effect of using different batches of UHPC premix, shows the same shrinkage as 4NB03W in the earlier stages and then slightly less shrinkage in the later stages. As can be seen in the third plot of Figure 5.4, gage 4NAMS0 is more restrained and thus shows less shrinkage than gage 4MCMSD.

#### **5.1.5 Discussion of Results:**

- Shrinkage strains are very closely tied to the temperature conditions to which the girder is exposed. The temperature of supplemental heating and the proximity of conduits are also factors that have been seen to affect the shrinkage of UHPC. The coefficient of thermal expansion of fresh concrete is a point of concern as it is likely to affect the strains in the girder due to temperature variations.
- The location within the girder and the restraint to which the concrete is subjected also influence the shrinkage activity as seen by the comparison of strains shown by the lateral deck gage, the web gage and other transfer gages. Release of

formwork has been seen to spark shrinkage activity at some locations in the girder.

- Theoretically the shrinkage effect under controlled conditions should be approximately the same along the entire girder. However, the conditions existing while the girders were cast were not completely controlled and more shrinkage was observed at the surface on top and at the surface in contact with the forms and it reduced downwards from the top and away from the ends.
- Mixing of different age premixes also affects the shrinkage rates as was seen in Girders 3 and 4. The different setting times of the premixes seem to release quite a lot of the restraint, thereby allowing the concrete to shrink much earlier than when the forms are removed.
- Table 5.1 summarizes the shrinkage activity of the girders in different stages and the temperature and supplemental observations that define the overall behavior of the girders.
- Table 5.2 summarizes the important stages during the fabrication of the girders that were instrumental in defining the shrinkage behavior of the girders.
- Table 5.3 includes some additional features related to shrinkage observed from the plots for the shrinkage behavior of the girders.

Table 5.1 Summary of Shrinkage Results

<b>Stage</b>		<b>Girder 1</b>	<b>Girder 2</b>	<b>Girder 3</b>	<b>Girder 4</b>
<b>Pre-Set</b>	Hours	0 – 15	0 – 10	0 – 20	0- 30
	Temperature	Reduces	Reduces	Increases constantly	Increase
	Shrinkage	No Activity	Hardly any shrinkage	No shrinkage	Shrinkage starts slowly
	Extra Shrink.				
<b>Primary Shrinkage</b>	Hours	15 – 25	10 – 30	20 – 40	30 – 45
	Temperature	Marked increase	Constant	High Increase	Reduces and steadies
	Shrinkage	Expands	Hardly any shrinkage	Noticeable shrinkage	Slight exp. then steady
	Extra Shrink.	1SA12I	2NB03W, 2NA20I	3NB03W, 3MCMSL	4NB03W, 4MCMSL
<b>Intermediate Shrinkage</b>	Hours	25 – 34	30 – 45	40 – 64	45 – 58
	Temperature	Falling	Reduces	Reduces 0.67°C/hr	Rise
	Shrinkage	Slight Shrinkage	Slight Exp, then Shrink	Slight Expansion	Shrinkage – 10 µε/hr
	Extra Shrink.				
	Hours	34 – 45	45 – 55	64 – 70	58 – 70
	Temperature	Rises - 1°C/hr	High rise - 3°C/hr	Increases 1.75°C/hr	Reduces - 1°C/hr
	Shrinkage	Shrinkage – 11 µε/hr	High Shrink.– 24 µε/hr	High Shrink.–12 µε/hr	Expands – 15 µε/hr
	Extra Shrink.				
<b>Secondary Shrinkage</b>	Hours	45 – 55	55 – 65	75 – 115	70 – 80
	Temperature	Constant and decline	Steady and falling	Gradual Increase	Increase 2.25 °C/hr
	Shrinkage	Shrinkage reduces	Shrink. reduces rapidly	Slow Shrink. – 3 µε/hr	Rapid Shrink–15 µε/hr
	Extra Shrink.				
	Hours	55 – 69	65 – 68	115 – 137	80 – 95
	Temperature	Reduces	Reduces rapidly	Reduces Rapidly	Reduces
	Shrinkage	Expansion occurs	Rapid expansion	Expansion	Slight Expansion
	Extra Shrink.				

Table 5.2 Stages During Fabrication of Girder

Stage in Casting	Time After Casting (hrs.)			
	Girder	Girder	Girder	Girder
Overhang Blockouts	24	30	40	35
Lateral Shrinkage Cracks Observed	25	-	-	-
End Blockouts Released	30	30	40	35
Turnbuckles Released	30	38	45	35
Low Temperature Steam Started	34	38	0	0
Top and Bottom Clamps Released	46	50	69	49
Side Forms Broken Loose	46	51	70	49
Strands Cut	69	60	137	95

Table 5.3 Additional Features Observed

Feature	Girder	Girder	Girder	Girder
Gages showing more early shrinkage	1MCMSL & 1SB03W (22 $\mu\epsilon$ /hr)	2MCMSL & 2NB03W (36 $\mu\epsilon$ /hr)	3MCMSL & 3NB03W (27 $\mu\epsilon$ /hr)	4MCMSL, 4NB03W & 4SB03W (30 $\mu\epsilon$ /hr)
Gage showing highest temperature	1SAMSO	2NAMSO	3NAMSO	4NAMSO
Comparison of Mid-span Longitudinal Gages (NAMSO and MCMSD)	1SAMSO shows more shrinkage activity	2NAMSO shows more shrinkage activity	3NAMSO shows more shrinkage activity	4NAMSO shows more shrinkage activity

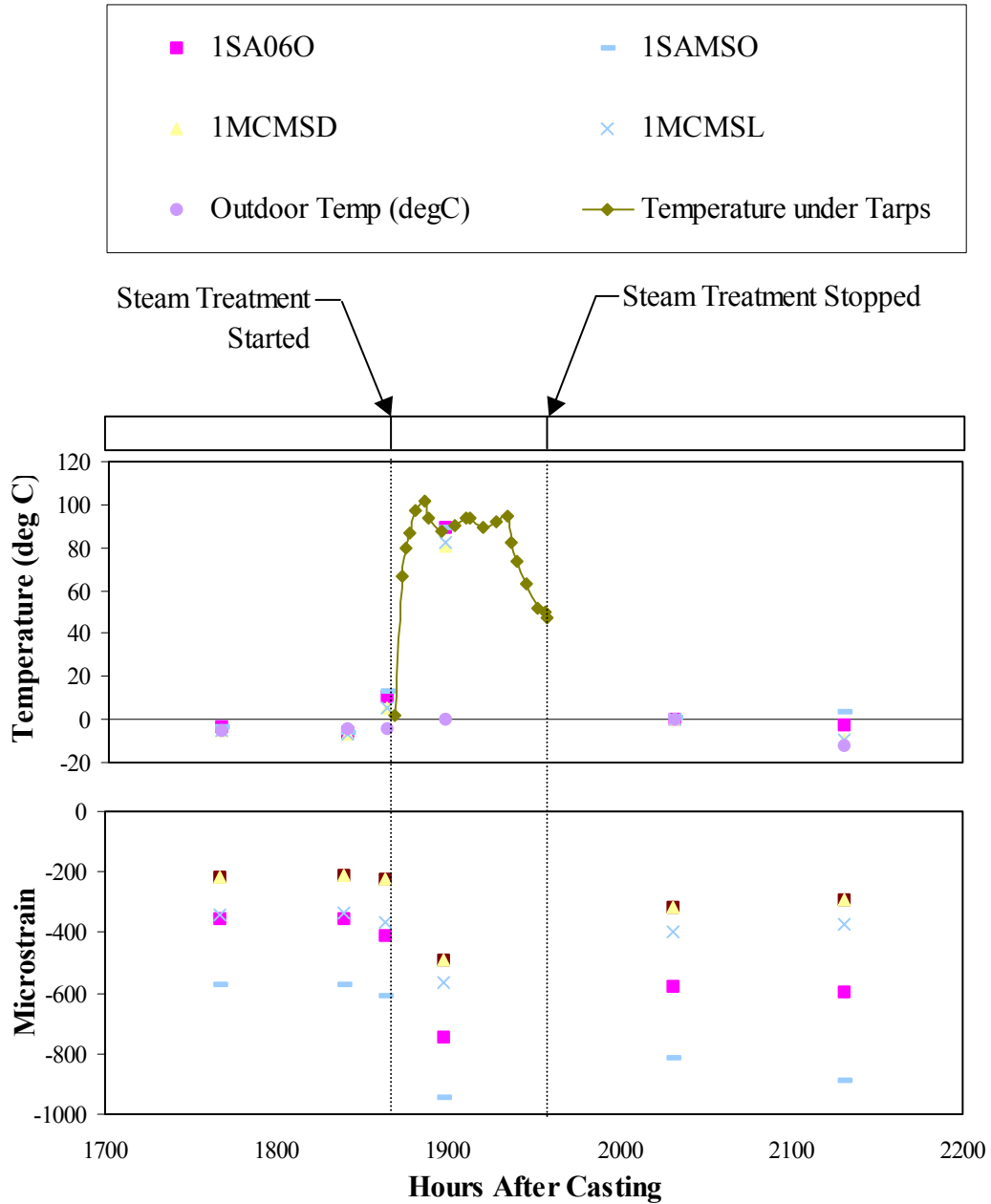
### **5.1.6 Effect of Steam Treatment:**

The steam treatment procedure was described in Chapter 4. The following details the shrinkage behavior resulting from the steaming of each girder.

#### ***Girder 1***

Girder 1 was steam treated beginning 1869 hours (78 days) after casting. For this reason virtually all early age shrinkage had already occurred. Figure 5.5 shows the temperatures and strain behaviors associated with the steam treatment. While the outdoor temperature remained below 0°C most of the time, the girder temperature rose rapidly due to the steam treatment. The girder was subjected to steam treatment for about 90 hours, of which approximately 48 hours were at the steam level while the remainder of the time it ramped up and down. The steam temperature was increased at the rate of 5°C/hr during the first 20 hours and the temperature measured on the top of the deck surface reached a peak value of 100°C. It then decreased slightly and remained relatively constant for the next 50 hours. The temperature inside the girder also rose rapidly at almost 2.5°C/hr and reached a peak value of 91°C after 30 hours. Shown in Figure 5.5 are the peak temperatures reached by the two deck gages 1MCMSD and 1MCMSL, are about 10°C less than the gages in the lower part of the girder and hence these gages showed slightly less shrinkage than the gages at other locations. This is due to the steam conduits releasing the steam under the girder. The steam was slowly removed from the girder and the girder tended to expand slightly during this period but did not return to its original presteaming volume. On average, the transfer region gages showed 170 microstrain of

shrinkage from the steaming treatment, while the midspan deck longitudinal gage showed 98 microstrain of shrinkage.



**Figure 5.5 - Shrinkage Due to Steam Treatment, Girder 1**

## Girder 2

As seen in Figure 5.6, before the application of steam treatment to Girder 2, the shrinkage progressed at a negligible rate of 0.25 microstrain/hr. The girder was subjected to steam treatment 1845 hours (77 days) after being cast and the steaming was done for 72 hours.

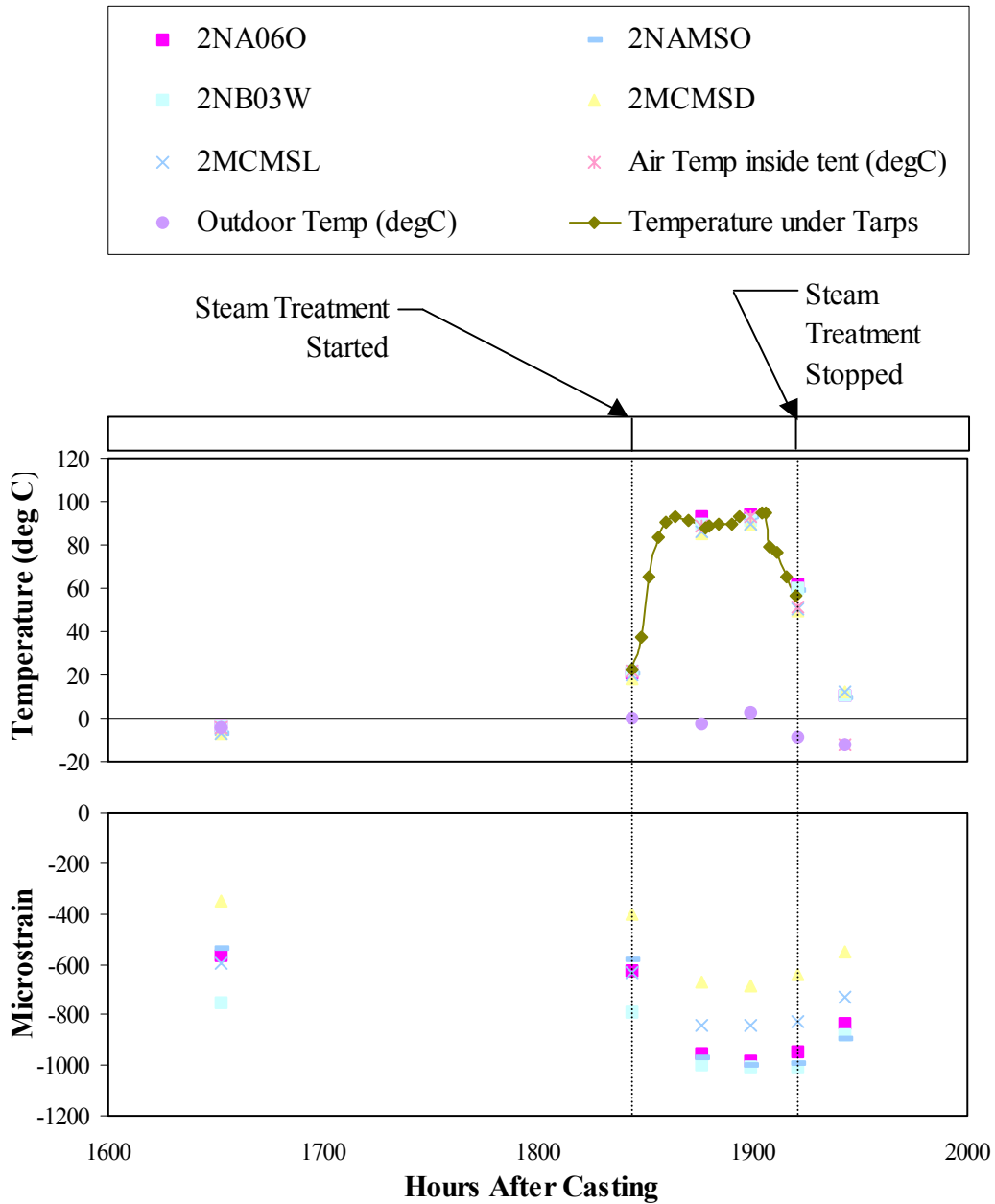


Figure 5.6 - Shrinkage Due to Steam Treatment, Girder 2

Figure 5.6 shows the temperature and the strain behaviors associated with the steam treatment. Figure 5.6 shows that the outdoor temperature, the air temperature inside the tent and the temperature inside the girder are almost the same before the steam treatment was started. Once steaming was initiated, the temperature on top of the girder increased at approximately 3.5°C/hr and reached 93°C 20 hours later. The temperature was then kept almost constant for the next 40 hours. It can again be seen in Figure 5.6 that the gages in the deck, i.e., gages 2MCMSD and 2MCMSL, show a peak temperature which was about 8°C lesser than that shown by the other gages. After this period the temperature was reduced and the girder showed a slight expansion. On average, the transfer region gages indicated 250 microstrain of shrinkage from the steaming treatment, while the midspan deck longitudinal gage showed 153 microstrain of shrinkage.

#### **5.1.7 Discussion of Results:**

- Shrinkage of the girder at different locations seemed to be affected by temperature variations due to the steam curing and relative differences of steam exposures near and away from the source (conduits at the bottom). The concrete in contact with the form was subject to higher temperatures and variations in shrinkage due to the heating and retention of heat by the forms.
- The part of the UHPC girder subject to a lower temperature of steam treatment showed less shrinkage as has been discussed in both girders.
- The girder tended to expand once the steam treatment was stopped but did not recover its original pre steam treatment volume.



## **5.2 Transfer Behavior**

### **5.2.1 Introduction:**

The focus of this section is the behavior of UHPC girders under the application of prestressing force. The key areas of discussion in this section are the significance of transfer analysis, prestress application to the girders, and the transfer behavior of each of the girders. The section on transfer behavior of the girders discusses various aspects of transfer analysis and a comparison with analytically predicted strains. Determining the transfer length for the strands was also one of the aims of the analysis.

### **5.2.2 Background:**

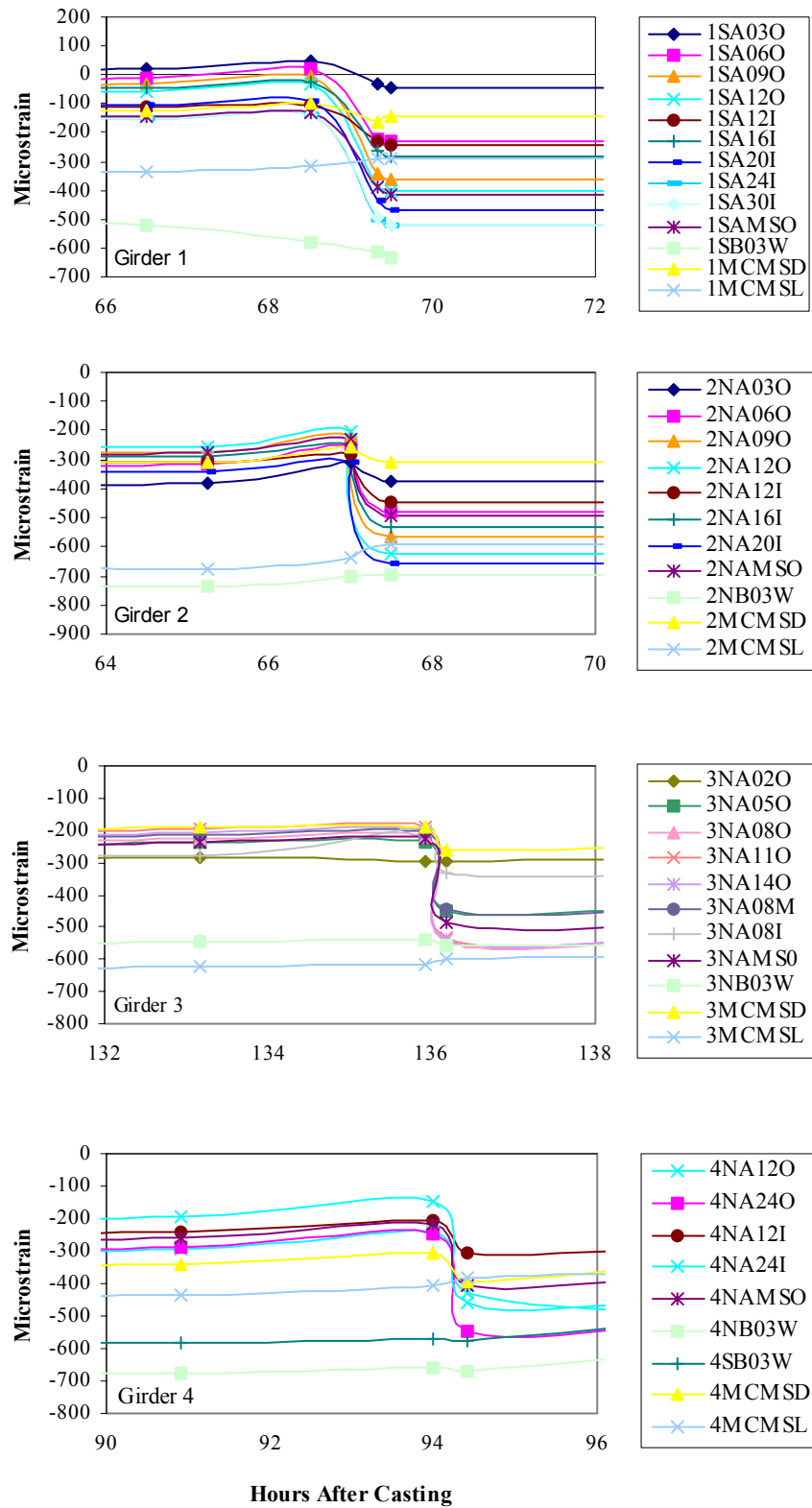
Vibrating wire gages installed in each girder were used to record the transfer behavior of the UHPC girders. Of particular interest to this study was the determination of the optimum transfer length for prestressing strands in UHPC. The gages installed at the east end in the bulbs and the gages installed at the midspan in the bulb were the primary source of strain data. These gages were tied to strands but were embedded in the UHPC matrix and thus are considered to be accurate representations of the strain in the UHPC at those locations. Prior test results for the transfer of prestress into UHPC are limited; however, one earlier study (*Steinberg E., Lubbers A., 2003*) showed a length of about 10 in. was considered sufficient for the complete transfer of prestress in this UHPC.

The prestressing strands were stressed in the girder formwork prior to the final form setup and at least one day prior to casting. As such, they were exposed to temperature and

other atmospheric variations before the girder was cast. Even after the girder was cast, the prestressing strands were subject to varying temperature profiles along their length as the exposed length of strand between the girder and the bulk-head was subject to the ambient temperature, whereas the strand embedded in the unhardened UHPC was subject only to controlled temperatures inside the tent due to the application of supplemental heating.

### **5.2.3 Application of Prestress:**

As stated in Chapter 4, low relaxation strands 0.5 in. in diameter were used for the prestressing. They were pulled based on force and elongation calculations with 19 in. and 21 in. as the specified minimum and maximum elongation of the strands. All strands were pulled to 29.2 kips of force. The prestressing was applied only after ascertaining that the UHPC had gained at least 10 ksi of compressive strength. The strands were cut symmetrically in both bulbs and simultaneously at each end. Figure 5.7 shows the strain values in all four girders at the time the strands were cut. The strains in all four girders are steady before the sudden drop in strains is observed in the plots for each of the girders. The actual drop in strains is more characteristic of the plot seen for Girder 3 but the slope of the drop looks variable for the girders due to different time intervals of data recorded after the strands were cut. All the gages placed longitudinally show increased compressive strains at the time of release of prestress. The two gages placed in the deck at midspan and the web gages are not near the strands in the girder. The web gage in the



**Figure 5.7 - Strain Profile During Application of Prestress**

four girders show compression. The longitudinal deck gages surprisingly show significant compressive strains in all four girders whereas the lateral midspan gage shows slight expansions in all the girders indicating lateral tensile strains in the deck slab at the midspan. These three gages are not prominently considered in the subsequent transfer analysis.

#### **5.2.4 Comparison of Strains Before and After Prestressing:**

As per the prestressing pattern discussed in earlier chapters, the outer bulb had more strands that were not debonded as compared to those in the inner bulb. Collection of data was concentrated in the region of transfer of the first set of strands (not debonded) and the second set of strands (debonded up to 12 in. from support) in the first two girders. Hence, in Girders 1 and 2 the strain gages were located in the first 12 in. in the outer portion of the bulb and in the next 8 to 18 in. of the inner portion of the bulb. Girders 3 and 4 did not have a series of gages in the inner bulb for recording the transfer profile of the second set of strands. Figure 5.8 shows the strain readings before and after the prestressing strands were released and the net strain change in the bulb region as a result of the prestressing process. Shown are the separate plots created for the outer and inner bulbs for Girders 1 and 2, as there is a change in the strain pattern. The net increase in strain due to prestress shows increasing values up to 9 in, from the support after which the strain values show negligible increases suggesting that full transfer has been achieved at around 10 in. from the support.

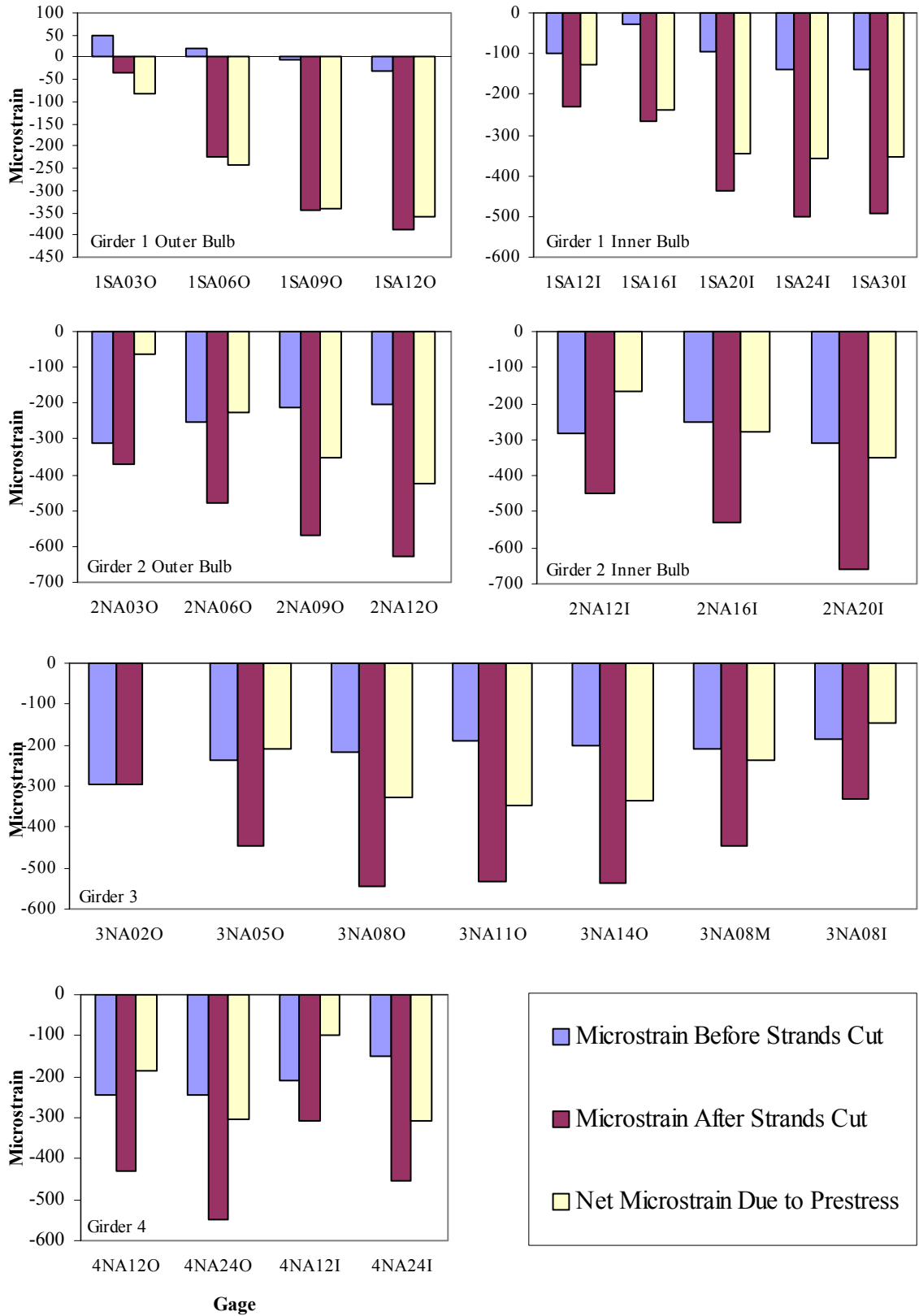
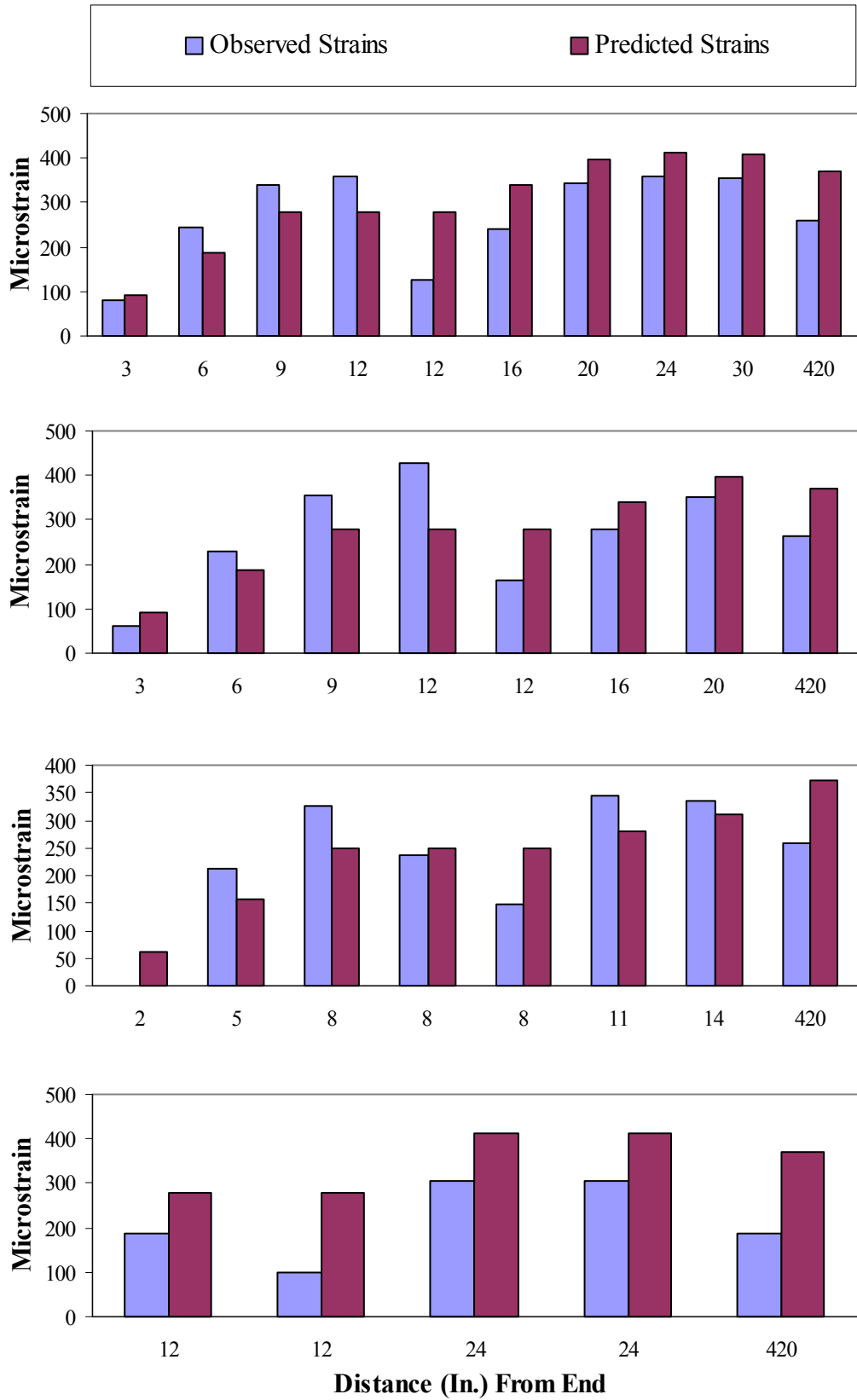


Figure 5.8 - Strains Before and After Prestressing

After that the prestressing strain is seen to decrease, as shown in the mid-span gage of all four girders and at the closer location of gage 3NA14O in Girder 3. Ideally, the gages at 12 in. in the inner bulb should have the same strain increase as the gage at 12 in. in the outer bulb. But, on comparing the outer and inner bulb strain plots it can be seen that there is a large difference in values, indicating a lag in the transfer across the section. The strain at 12 in. in the inner bulb is about 230 microstrains less than that at the same location in the outer bulb. Even though the number of strands transferring stress to the section at 12 in. from support increases by 50% at 12 in., we do not see the same pattern in strains. The six strands, which are not debonded, appear to have transferred completely before the three strands in each bulb debonded up to 12 in., start transferring the prestress. The strains for the inner bulb also show high increments between 12 in. and 20 in. after which the increase is marginal, again indicating a transfer length of about 9 in. to 10 in. The strain plots for the gages at 8 in. from support (3NA08O, 3NA08M and 3NA08I) in Girder 3 and gages at 12 in. (4NA12O and 4NA12I) and 24 in. (4NA24O and 4NA24I) in Girder 4 also highlight the difference in transfer across the section.

#### **5.2.5 Observed Strain Patterns and Linear Transfer Approximation:**

As it was known from earlier studies that the strands would completely transfer the prestress at about 10 in., analytical calculations were carried out for comparison with the strains observed in the girder. Figure 5.9 shows the comparison between the observed and the predicted strains. The predicted strains are a linear approximation that assumes that the prestress is transferred linearly up to complete transfer at 9 in. The plots for



**Figure 5.9 - Observed and Predicted Strains**

Girders 1 and 2 show that the prestress strain is higher than expected in the first 12 in. The observed strains at 12 in. in the outer bulb are about 60-80  $\mu\epsilon$  higher than expected in Girders 1 and 3, whereas in Girder 2 the observed strains are 150  $\mu\epsilon$  higher. The strains at 12 in. in Girders 1, 2 and 3 are even higher than the total strain that can be transferred by the total prestressing force in the non-debonded strands available at that section. Since the assumed transfer length for the analytical calculations is 9 in., the predicted strains at 9 in. and 12 in. in the outer bulb and 12 in. in the inner bulb are the same. However, the observed strains show some increase even after 9 in. and a large drop at 12 in. between the outer and the inner bulb. The observed strains at 12 in. in the inner bulb are about 150  $\mu\epsilon$  lower than expected in Girder 1 and about 110 microstrain lower than expected in Girder 2. After 12 in. three more strands in each bulb start transferring prestress but the strains in the inner bulb are much less at 12 in. in comparison to the outer bulb and shows significant increases up to 20 in. and slight increases after that up to 24 in. As can be seen in the plot for Girder 1, the strains show a drop after 24 in. as the gages at 30 in. and midspan show lesser strains. In Girder 2, the strains increase between 12 in. and 20 in. and the strain at midspan is much less. The theoretically predicted strains assume that the strains due to transfer of prestress keep accruing with every set of transferring strands and are maximum at about 7 ft. from the end when all the strands have reached complete transfer. The expected strain at midspan is slightly less than that at 7 ft. because of the self-weight flexural forces being maximum at midspan. The observed strains in Girder 3 also follow a pattern similar to the other girders with strains increasing rapidly up to 8 in., increasing slightly between 8 in. and 11 in., and reducing for some length after that even though the number of strands transferring increase. Also



the strains at 8 in. in the middle and inner portions of the bulb are less than that at the outer portion. The plot for Girder 4 also shows another interesting observation: there is a difference in the strain values in the outer and inner bulbs at 12 in. (where only the 6 non-debonded strands in each bulb have transferred) but the strain values in the inner and outer bulbs at 24 in. (where the 6 non-debonded and the three strands debonded up to 12 in. have transferred) are almost the same with the inner bulb value being slightly higher. This may indicate that the strains transferred may have lateral variations in the transfer regions due to various debonding patterns. However, at a location, i.e., at 24 in., where prestress has already been transferred almost symmetrically throughout the section, the observed strains show little lateral variation at a particular longitudinal location. Another important observation is that the observed strains in all the girders, except Girder 4, are particularly higher than the predicted strains in the first 12 in., and the strains at 12 in. are higher than the predicted possible maximum strains. This may point to imperfect debonding since the higher strains may be due to prestress contributions from the debonded strands. Figure 5.10 shows the strain profile of all the gages in the bulbs regardless of whether they are in the outer portion or the inner portion of the bulb and with the predicted profile. The first plot shows only the gages in the transfer region whereas the second plot also shows the strains in the gages at midspan. Here the reduction in the strains at midspan can be clearly seen.

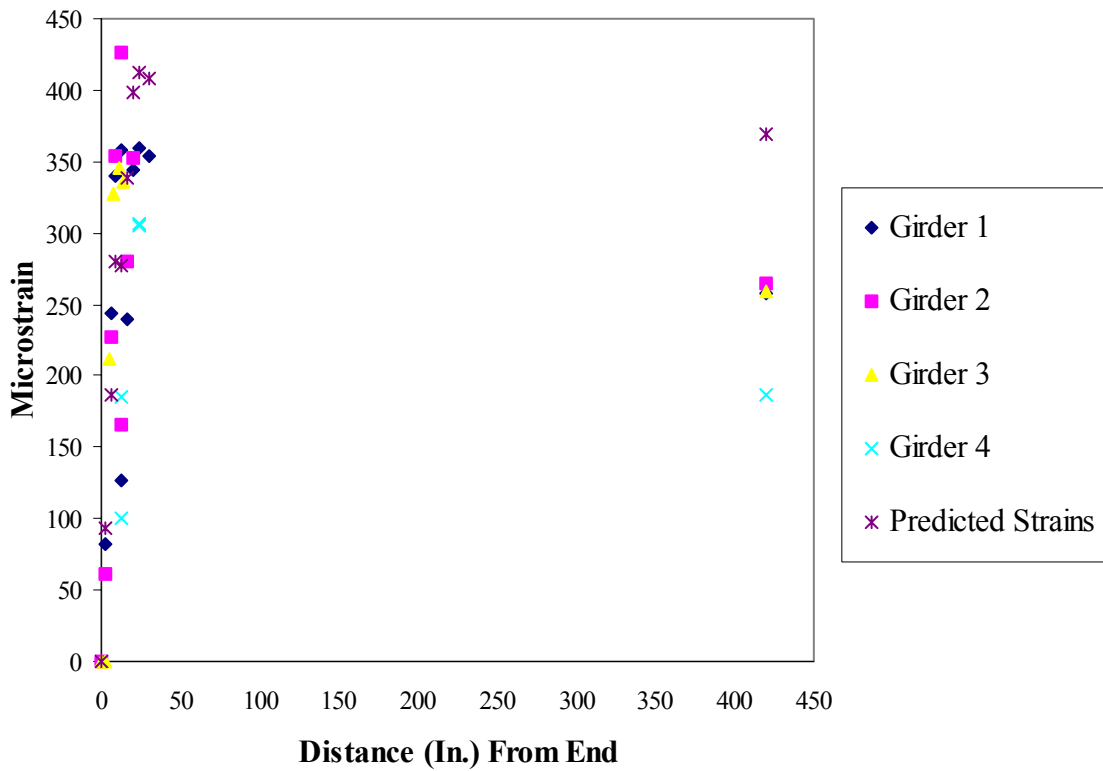
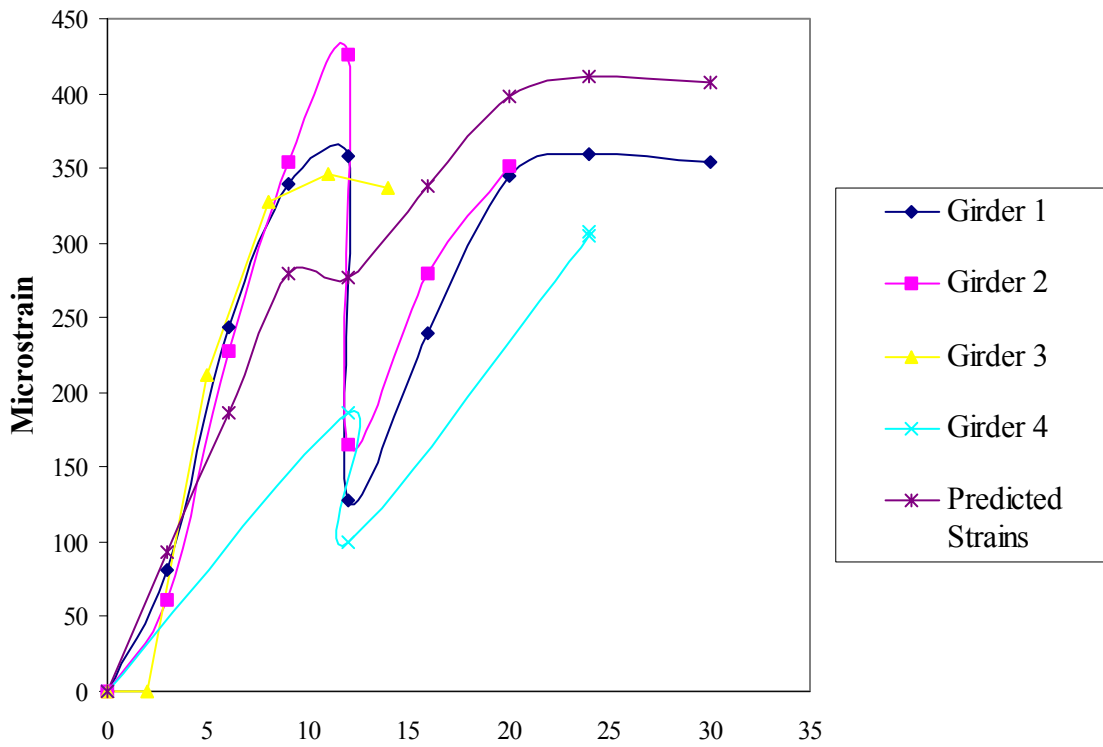
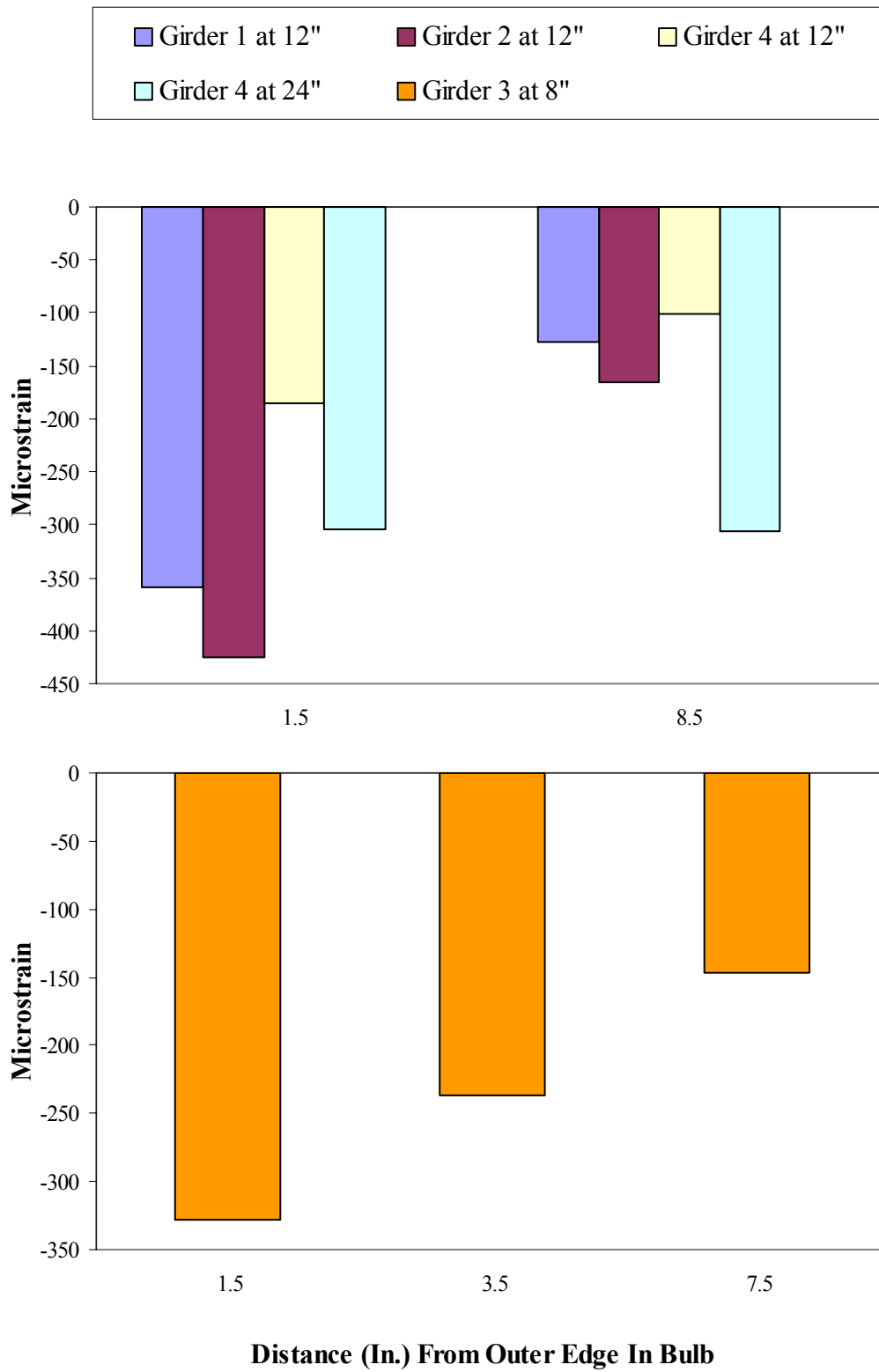


Figure 5.10 - Transfer Profile of All Bulb Gages

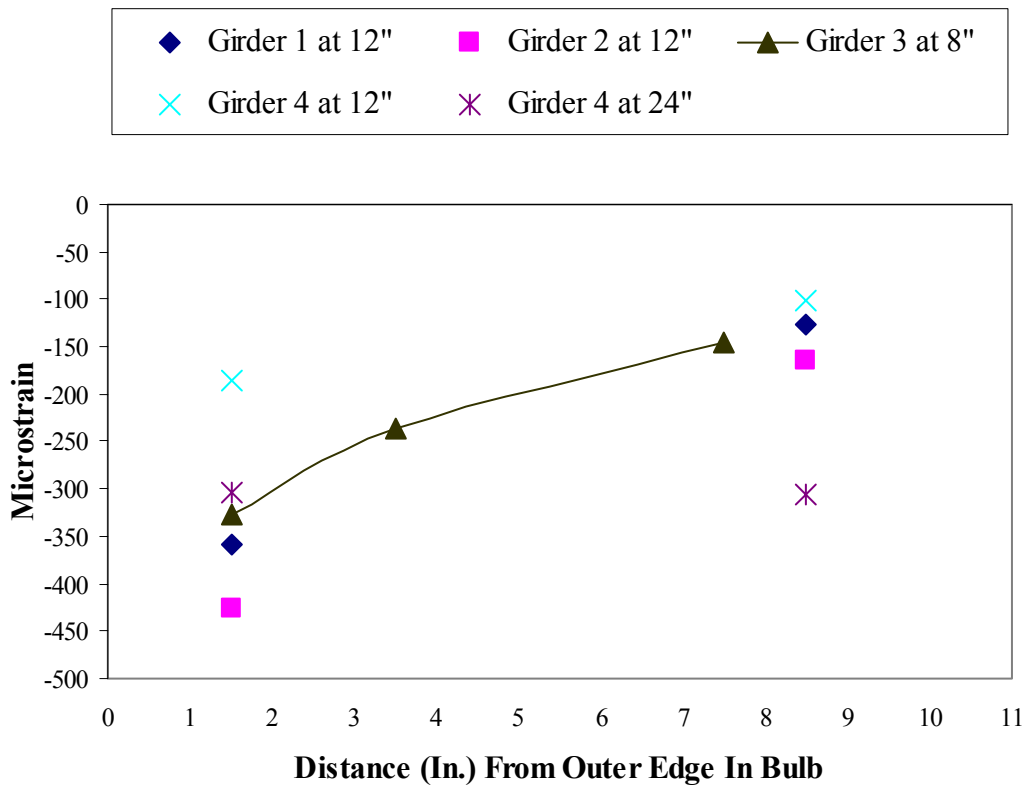
### **5.2.6 Transfer Strains Across the Bulb Section:**

As has been pointed out before, the strains in the concrete section are not uniform and are concentrated more in the region near the strands and less going away from the strands. Figure 5.11 shows the comparison of the strains in gages placed to monitor the prestress transfer in the bulb at the same longitudinal distance from the support but at different locations in the bulb cross section. The gages are placed in the outer portion (1.5 in. from the outer edge) of the bulb and the inner portion (8.5 in. from the outer edge or 2.5 in. from the inner edge) of the bulb. The first plot is for outer and inner bulb gages at 12 in. for Girders 1, 2 and 4 and at 24 in. for Girder 4. At 12 in., the first set of strands, which are more concentrated in the outer portion of the bulb, have transferred whereas, at 24 in., the second set of strands have transferred and the effective prestressing force is slightly more concentrated in the inner region of the bulb. There is a sharp reduction in the strain values at 12 in. between the outer and the inner bulb gages for all the three girders under observation. The reduction in strains is 230 microstrains, 260 microstrains, and 85 microstrains for Girders 1, 2 and 4, respectively. The web provides restraint to the prestressing force in the bulb and the restraint is more in the inner bulb than in the outer bulb. Also, due to the eccentric loading in the bulb in the first 12 in. there is lateral bending in the bulb with the outer bulb being under more compression while the inner bulb has less compression. However, at 24 in. the strain values do not show reduction at the inner portion. Instead, the strain at the inner bulb is slightly higher than the outer bulb, which is consistent with the prestressing force being slightly more concentrated in the inner bulb at 24 in. The second plot in Figure 5.11 shows the prestress strain in the three gages placed in Girder 3 at 8 in. from the end.



**Figure 5.11 - Difference in Transfer Microstrain Across the Section  
- Girders 1, 2, 3 and 4**

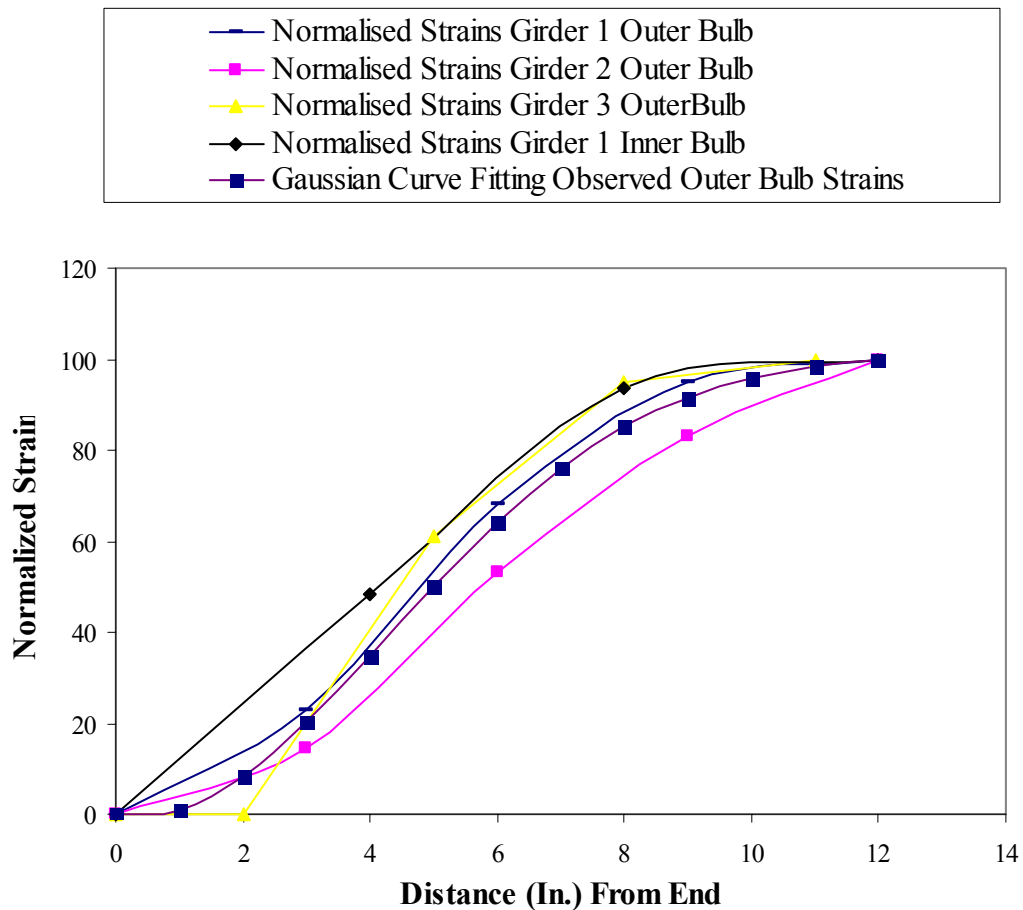
The gages 3NA08O, 3NA08M and 3NA08I are at 1.5 in., 3.5 in. and 7.5 in. from the outer edge in the cross section. We can see a 90 microstrains reduction between the outer and middle portion of the bulb and a further 90 microstrains reduction between the middle and the inner portion of the bulb. The fall in strain values across the section can be clearly observed. Figure 5.12, with an X-axis equal to 11 in. (width of the bulb), further elaborates the strain reduction in the cross section.



**Figure 5.12 - Difference in Transfer Microstrains Across The Section**

### 5.2.7 Normalized Transfer Strains:

The transfer of prestress along the length of the strands follows a pattern that can be approximated by using normalized transfer strains. Strains have been normalized assuming a 100% transfer at 12 in. and the observed strain values at intermediate distances are expressed as a percentage of the strain at 12 in. Figure 5.13 shows the normalized strain plots for Girder 1 outer and inner bulb gages and Girder 2 and 3 outer bulb gages. The transfer pattern is quite similar except that seen for Girder 3 at gage 3NA02O, which shows no strain due to prestress. The fifth curve in the figure is the



**Figure 5.13 - Observed and Gaussian Normalized Curves**

Gaussian curve, which fits well with the strain pattern shown by the UHPC in the girder bulbs. The Gaussian equation is as follows:

$$\varepsilon = a + b * \exp \left[ -0.5 \frac{(x-c)^2}{d^2} \right]$$

where: a, b, c, and d are constants.

$$a = -384.972$$

$$b = 386.865$$

$$c = 0.301$$

$$d = 4.023$$

x = distance from end in the transfer region.

### **5.2.8 Discussion of Results:**

The results and observations from the study of transfer behavior of UHPC girders can be briefly summarized as follows:

- The increase in strain due to prestressing is almost negligent after the strands have transferred for more than 9 in., indicating a transfer length of 9 in. to 10 in.
- The strain seen in the first 12 in. in the outer bulb is higher than the maximum strain that can be transferred by the number of strands available at that section. It indicates lateral flexure within the bulb, which produces additional bending strains and may be responsible for the compressive strains in the outer bulb being more than the maximum possible theoretical strain.
- The strain seen in the inner bulb in the first 12 in. is much less than that seen in the outer bulb, which may be due to the transferring strands being more

concentrated in the outer bulb in the first 12 in and causing compressive bending strains in the outer bulb.

- The strains observed at the midspan in the bulb are less than those seen at the ends where all strands have transferred, indicating a loss in prestress. This may be due to the restraint provided by the web all along the length of the bulb.
- The Gaussian curve fits well with the strain pattern observed in the girder bulbs.



## **5.3 Behavior at Midspan**

### **5.3.1 Introduction:**

This section deals with the behavior of the girder at midspan. Midspan behavior of the girder is affected by various factors such as shrinkage, creep, prestressing and dead weight of the girder. The section starts with stating the significance of the midspan behavior analysis and then considers the behavior at different stages of the UHPC girder life. These stages include: the behavior at early age, which is mainly due to the shrinkage in the UHPC girders; the behavior after application of prestressing force; and the behavior under steam treatment.

### **5.3.2 Significance:**

The UHPC in the girder is subject to various effects and forces such as shrinkage, prestress and creep. These forces and effects are dependent on various conditions such as temperature and time after application of prestress. The midspan of the girder is under the maximum prestressing force, creep and flexural effects. Hence, the study of the behavior at the midspan of the girder requires special attention. From the time the girder is cast, the UHPC is subject to shrinkage stresses mostly before hardening and prestress, and self-weight stresses after the UHPC has gained some strength. The shrinkage stresses vary according to locations in the girder as seen in the chapter on shrinkage and there can be unrestrained shrinkage or shrinkage at a restrained location. Temperature and supplemental heating also affect shrinkage rates of the girder. Prestress applied to the girder causes large variations in stresses at the midspan. Theoretically, the prestress

applied in the bulbs at the bottom should cause compression at the bottom and tension in the deck at the top. Cambers due to prestress, creep and self weight stresses are also significant factors affecting the overall behavior of the girder at midspan.

### **5.3.3 Early Age Behavior at Midspan:**

Three vibrating wire gages were installed at midspan; two gages placed longitudinally and laterally in the deck and one installed in the bulb. At an early age, the strain variations are only due to shrinkage of the UHPC. As seen in Figure 5.14, the midspan shrinkage rates are almost the same as those seen in other locations such as the bulb transfer and web regions of the girders. Shrinkage rates of UHPC girders are greatly influenced by the temperature variations in the girder but the gage placed laterally in the girder deck at midspan shows sensitivity to its location in the girder and formwork conditions. The lateral gage in the deck is in such a location that it is fully restrained before the formwork is released and it is unrestrained after the formwork is released. Hence, the release of inner forms also releases the lateral restraint of the girder deck, causing the lateral gage in the deck to show sudden increases in compressive strains. The shrinkage rates recorded by the lateral deck gage after the inner forms are released are 25 microstrains/hr in Girder 1 and 50 microstrains/hr in Girder 2. Girder 3 and 4 were subject to supplemental heating as soon as the fresh UHPC was placed and hence in these girders the temperature had much more effect on the shrinkage rates compared to those due to the formwork release. Also these two girders contained two different ages of premix, which seems to have relieved a lot of the restraint and allowed for the shrinkage

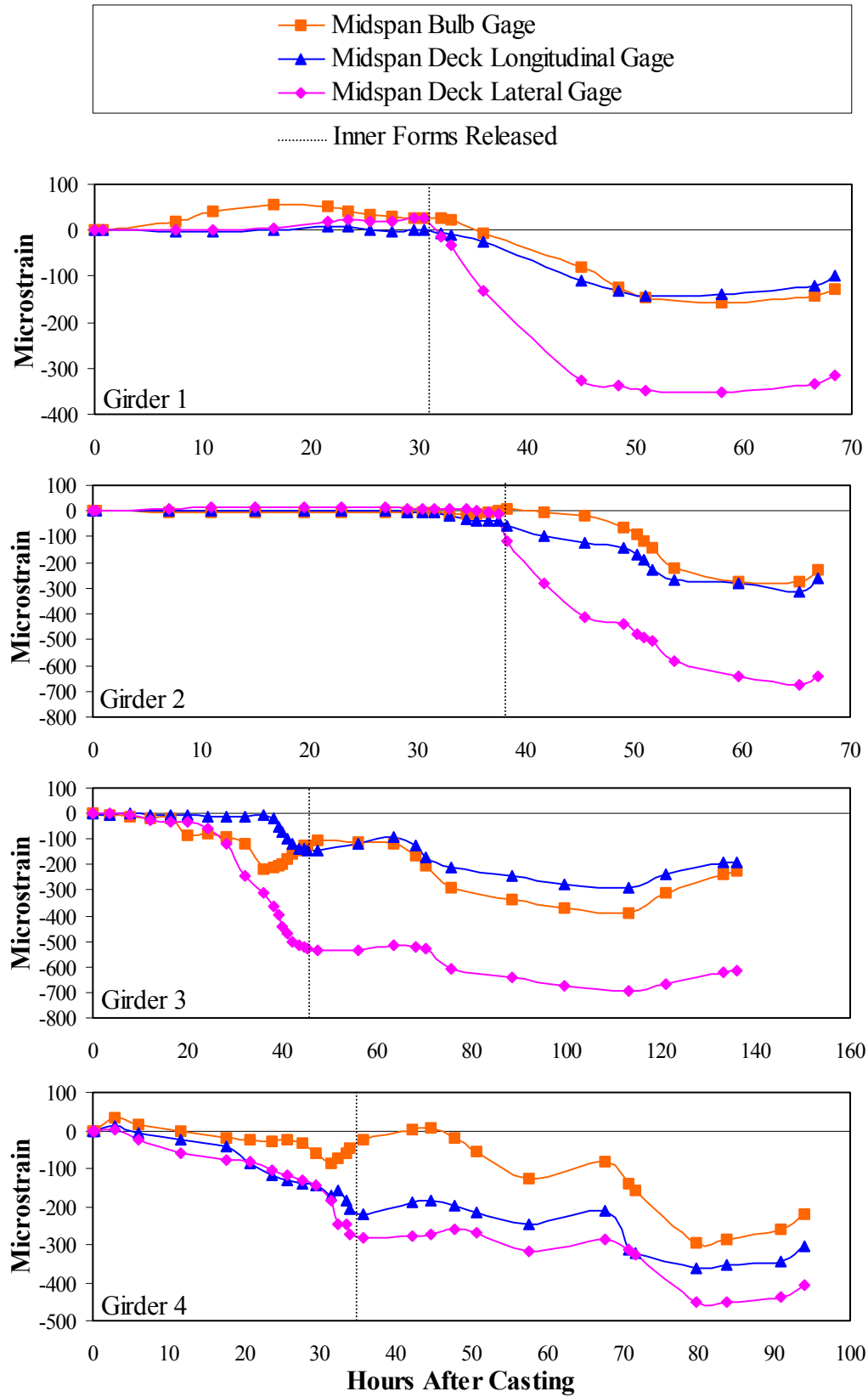


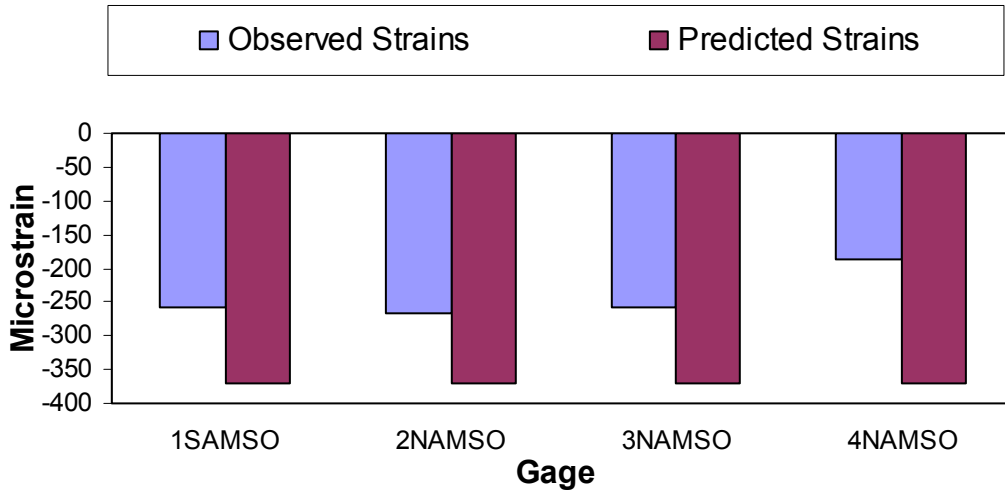
Figure 5.14 - Early Age Shrinkage at Midspan

before the release of forms. The bulbs at the bottom are also closer to the heating conduits and hence it can be seen that the strain in the longitudinal gage in the bulb shows much larger variations than the longitudinal gage in the deck. Also it can be seen in Girder 2 that the midspan bulb gage shows a much-delayed shrinkage response (which starts only after the supplemental heating is started) in comparison to the midspan longitudinal deck gage, which is comparatively less restrained. However, in Girder 3, which is subject to supplemental heating right from the start, the midspan bulb gage starts showing shrinkage much earlier than the other gages. As has been pointed out in the chapter on shrinkage, the midspan bulb gage also shows a higher concrete temperature as compared to gages at other locations.

#### **5.3.4 Behavior at Midspan After Prestressing:**

The prestressing pattern for all the UHPC girders is such that all the strands in the bulbs are completely transferred at about 7 ft from the ends. Hence, theoretically, the prestressing force is maximum between 7 ft. from either end and at midspan at the bottom. At the same time, the flexural forces which counter the prestressing forces are maximum at midspan also. Tension in the bulbs due to self-weight is almost negligible in comparison to the compressive prestressing forces. Hence, considering the effect of the self-weight of the girders, the compressive force in the bulb reduces slightly between 7 ft. (approximately where all the strands have transferred) from either end and the midspan. Once the prestress is applied, the girder cambers up and, at this point, the self-weight of the girder also acts along with the prestressing force. The midspan longitudinal bulb and deck gages show compression whereas the lateral midspan deck gage shows a slight

tension on the application of prestress. As observed in Figure 5.15, the midspan bulb gages do not show as much strain as analytical calculations suggest. The strains seen in the midspan bulb gage are about 110 microstrains lower than expected in Girders 1, 2, and 3 whereas they are about 185 microstrains lower than expected in Girder 4.



**Figure 5.15 - Observed and Predicted Prestress Strains at Midspan**

After prestressing the girders, they were blocked in the yard and the camber was measured. The camber of the bottom of the bulbs was recorded using a string line and a tape measure. Table 5.4 shows the camber values of the bottom of the bulbs of all the girders recorded at various times. It can be seen that the camber values show slight increase with time, thus pointing out that there might be creep effects on the girder.

Table 5.4 Camber values for Girders

Girder No.	Camber (in.)				
	Date	11/06/03	11/14/03	01/19/04	01/31/04
1	Age (days)	3	11	77	89
	North	-	-	1.500	1.875
	South	1.750	-	1.750	2.000
2	Age (days)	-	3	69	81
	North	-	1.063	1.500	1.750
	South	-	1.125	1.625	1.875
3	Age (days)	-	-	6	18
	North	-	-	1.500	-
	South	-	-	1.750	-
4	Age (days)	-	-	-	4
	North	-	-	-	1.000
	South	-	-	-	0.500

**5.3.5 Midspan Behavior under Steam Treatment:**

The early age shrinkage of the girders occurred before the girders were given steam treatment. During steam treatment, as discussed in the chapter on shrinkage, the peak temperatures reached by the midspan deck gages are about 10°C lower than the other gages, which are closer to the steam discharging conduits. Accordingly, these two midspan deck gages show slightly less shrinkage than the other gages. Figure 5.16 shows the strains in the midspan gages and in one of the transfer gages in the girder during steam treatment. In Girder 1, the lateral deck gage shows 35 microstrains and the longitudinal deck gage shows 98 microstrains of shrinkage compared to that in the midspan bulb gage, which shows 200 microstrains and in the transfer gages which show

170 microstrains of shrinkage. In Girder 2 the shrinkage is more pronounced but the lesser shrinkage in the deck is evident as the lateral deck gage shows 97 microstrains of shrinkage and the longitudinal deck gage shows 153 microstrains of shrinkage compared to the midspan bulb gage which shows 308 microstrains and to the transfer gages, which show 250 microstrains of shrinkage.

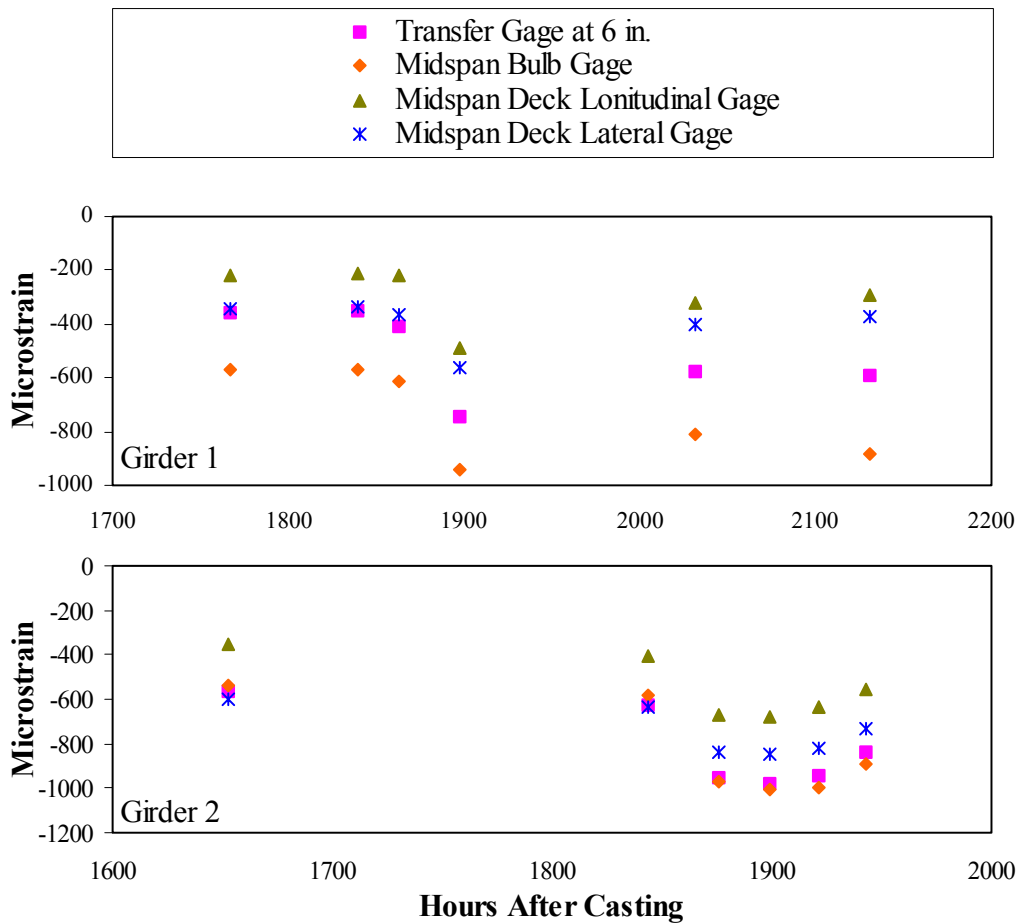


Figure 5.16 - Strains at Midspan During Steam Treatment

### **5.3.6 Discussion of Results:**

- During the early age shrinkage, the removal of formwork and temperature play an important role. The midspan lateral gages show increased shrinkage once the restraint provided by the formwork is removed whereas the midspan bulb gage shows greater shrinkage activity as the surrounding concrete is exposed to higher temperatures than at other gages.
- The midspan longitudinal bulb gage shows compressive strain lower than expected when the strands are cut whereas the lateral deck gage at midspan shows slight tension.
- During steam treatment, the midspan deck gages show lesser shrinkage, which may be due to the lower steam temperature that they are exposed to during the steam treatment.



## **5.4 Creep Behavior**

### **5.4.1 Introduction:**

This section talks about the behavior of the girder due to creep effects under the sustained prestressing loads. It starts with giving the background on the forces and conditions to which the girders are subject to that might be conducive to the formation of creep in the girders. In the later section, the creep effects on the first two girders are studied. Lastly, locations in the girder likely to be under maximum creep and hardly any creep are compared to check the creep effects.

### **5.4.2 Background:**

UHPC has been known exhibiting very low creep (P. Acker, 2004). As soon as the prestressing force is applied, the girder is under the influence of large compressive forces, which are concentrated in the bulbs that are at the bottom of girder. The immediate effect of cutting the strands is that the bulbs and in general the whole girder shows compressive strains. It is accompanied by an upward camber while the girders are still in the casting frame. The prestressing force is a sustained load, which continues to act when the girders are lifted and blocked in the yards in a simply supported position. It is during this stage the creep effects are being studied in this section. All the girders were cast and prestressed at different times and were blocked for different durations. Hence, the creep effects on the girders should be different. Also the location of the gages in the girder showing the strains is also important with respect to the proximity to strands and the influence of prestress.

### **5.4.3 Strain Increase After Application of Prestress:**

As soon as the strands are released, the girders were blocked in the yard. Girders 1 and 2 stayed blocked in the yard for long periods of time. During this stage, the forces acting on the girder were the self-weight and the prestress. Though most of the shrinkage occurs in the early stages after the concrete is cast, there is some residual shrinkage, which occurs at a very slow rate on a continuous basis over a large period of the concrete life. Figure 5.17 shows the strains in the girder during the period it was blocked in the yard with the prestressing force and self-weight acting on the girder. It can be seen from plots for Girders 1 and 2 that the compressive strains are increasing even though there is no increase in the forces acting on the girder. It can also be seen that there is a hiatus of almost 1500 hours in the plots for both the girders during which the strain values are not available and the strain profile has been assumed to be an almost straight line. Hence, it is very difficult to state the actual strain in that timeframe though there shouldn't be any jump as the conditions were more or less constant. However, it can be seen that the compressive strains have increased over that period. It can also be seen, particularly in Girder 2, that the gage in the web at the end shows very little increase in strain. The midspan deck lateral gage also does not show much increase in strain. The increase in strain was approximately 75 microstrain over a period of about 1500 hours in Girder 1, whereas the increase in Girder 2 was around 80 microstrain over a period of about 1600 hours.

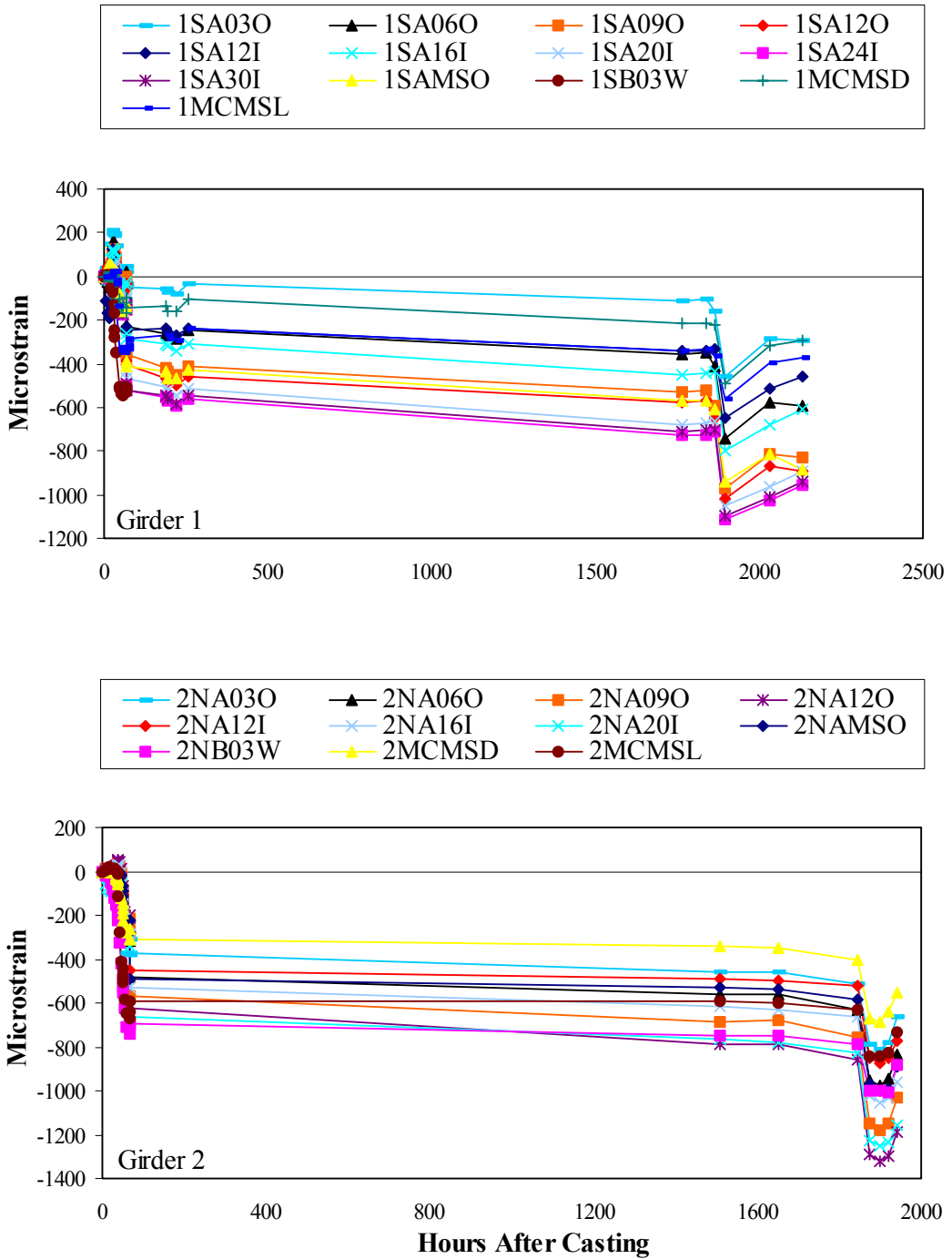
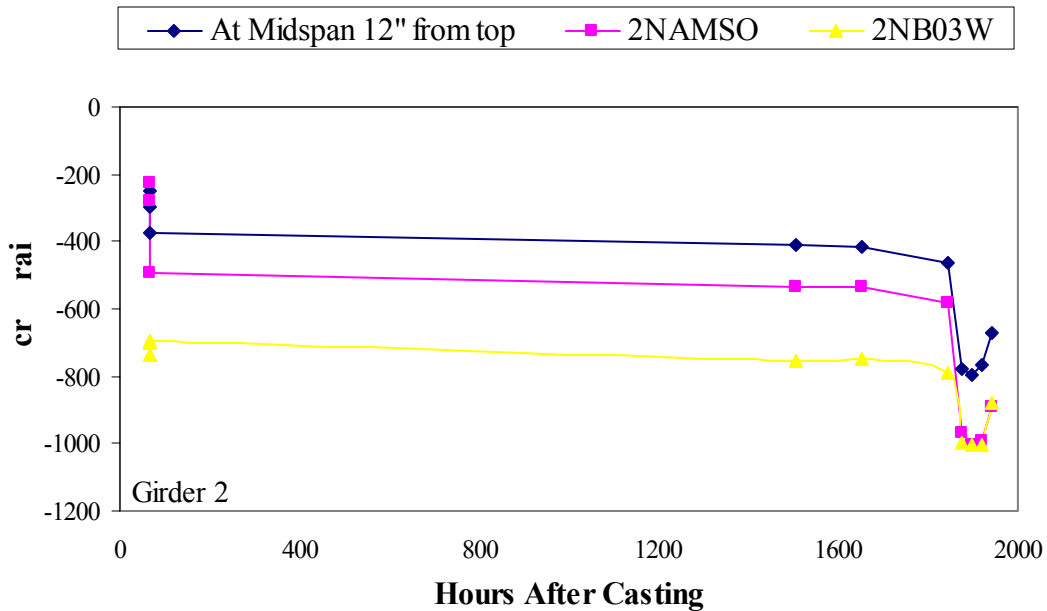


Figure 5.17 - Strains After Application of Prestress

#### **5.4.4 Strain Comparison Along the Neutral Axis:**

An approximate method of observing the creep strains is to compare the strains at locations not under the prestressing force and locations under prestressing force. In this section the strains along the bending neutral axis are discussed to get a closer idea of the creep acting on the girder. The web gage 3 in. from the east end of the girder has been placed at 12 in. from the top of the deck. This depth is approximately coincident with the bending neutral axis of the girder section. Hence, strains in this depth will be more or less an effect of the prestress. There are gages at midspan in the deck at the top and in the bulb at the bottom. The strain values in these gages have been interpolated to get the strain at 12 in. from the top at midspan. Figure 5.18 provides plots for strain at neutral axis at the end and at midspan, for Girder 2.



**Figure 5.18 - Strains along Neutral Axis and at Midspan in Bulb**

Another plot in the graph is of the strains in the bulb at midspan. It can be seen that the increase in the strains at 12 in. from the top is almost the same at the ends and at the midspan. The end gage 2NB03W is 3 in. from the east end and hence is more or less not under the influence of the prestressing force which can be seen in the plot as there is no drop in strains when the strands are cut. Hence, there should hardly be any creep effects near the end gage. And since the strain increase at midspan at the same depth from the top as the end web gage is almost the same, the creep forces don't appear to be significant.

#### **5.4.5 Discussion of Results:**

- An increase in the strains in the girder is seen over a period of 1500 hours (approximately 2 months), during which time the girders were kept blocked in the yard.
- The increase in strain was approximately 75 microstrain over a period of about 1500 hours in Girder 1, whereas the increase in Girder 2 was around 80 microstrain over a period of about 1600 hours.
- A comparison of locations where there is very little effect of the creep causing forces and locations under such forces, led to the observation that the strain increase at both locations have been almost the same. It indicates that the creep has not had much influence on the strains yet.

## Chapter 6 – Conclusion

### **6.1 Summary:**

The motivation for this research has been the need to provide solutions to bridge design problems and to meet the traffic, maintenance and economical demands of the current and future time. This study has been another contribution in Federal Highway Administration's (FHWA) efforts to develop improved bridges that can meet and adapt to current and future traffic, minimize environmental impact, require low-maintenance and are economical and easy to install. Ultra High Performance Concrete (UHPC), based on its material properties research phase, has been the material that has shown promise in satisfying these objectives.

The four optimized girders have been cast and monitored for the characterization of UHPC behavior in bridge girders. These girders were monitored during the early stages for shrinkage, prestress transfer and creep. Two of the girders have been set up on abutments to make a bridge and will be tested by passing AASHTO trucks for stresses, deflections and similar load related properties while at the same time will be continuously monitored over years for fatigue, shrinkage and creep to provide a thorough characterization of the UHPC bridge. The other two girders will be destructively tested in the FHWA structural lab; flexure, one-way shear and punching shear being the prospective tests. These will go a long way in understanding the minutes of the UHPC material behavior in bridge girders.

## **6.2 Conclusions:**

From the results obtained and discussed during the research, a number of conclusions can be drawn:

1. The shrinkage is very closely tied to the temperature conditions surrounding the girder and showed more shrinkage at higher temperatures. Even factors such as the variations in the temperature of supplemental heating along inside the tent and proximity to steam conduits affect the shrinkage rates.
2. The concrete at some locations in the girder have also shown variable shrinkage and the restraint to the concrete, particularly due to the formwork, also influences the shrinkage rates.
3. Mixing of different age premixes also affects the shrinkage rates. The different setting times of the premixes seem to release quite a lot of the restraint.
4. The transfer length was in the region of 9 in. to 10 in.
5. Lateral flexure within the bulb due to asymmetric prestress pattern, which produces additional bending strains may be responsible for the compressive strains in the outer bulb being more than the predicted maximum possible theoretical strain.
6. The Gaussian curve fits well with the prestress strain pattern observed in the girder bulbs.
7. There were no significant creep effects on the girder after almost 2 months since the application of prestress.

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