THERMAL GRADIENTS AND THEIR EFFECTS ON HIGH STRENGTH-SELF CONSOLIDATING CONCRETE BRIDGE GIRDERS

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ABSTRACT

An on-site instrumentation program to measure the thermal gradients in precast prestressed high strength-self consolidating concrete (HS-SCC) was conducted Bridge A7957 located on Highway 50, near Linn, Missouri, USA. Vibration wire strain gauges (VWSG) with built in thermistor to record concrete temperature were installed in the bridge girders and the deck slab in specific points of interests. Data concerning temperature gradients and thermal induced strains through the HS-SCC girders were monitored over a two-year period. Comparisons were made between design thermal gradients (NCHRP Report 276 and AASHTO LRFD) and those measured in-situ within the HS-SCC girders and the cast-in-place deck.

Keywords: High Strength-Self Consolidating Concrete, Thermal Gradient, Health Monitoring, Precast Prestressed Girders, NCHRP report 276.

INTRODUCTION

High strength-self consolidating concrete (HS-SCC) is a new innovation that has been developed by civil engineers to have all benefits of self-consolidating concrete (e.g., as flowability and stability) with the added benefit of increased strength[1,2,3]. It is beneficial because it can pass through and encapsulate the reinforcing steel, even in congested steel areas. The HS-SCC type has modifications on material proportions (e.g., reducing content and size of coarse aggregate, and increasing in the paste volume to enhance fluidity). Material properties are one of the several factors that can influence the heat of superstructure[4]. A question is raised here regarding SCC's constituent make-up and effect of fluidity on the structural behavior of HS-SCC. Thermal behaviors are examples of an area under investigation. The efficient design of prestressed concrete (PC) member needs to be well understood.

The daily temperature cycle leads to variation in the temperature distribution along the depth of the superstructure, which is generally a nonlinear variation. This leads to the development of thermal gradients in a structure[5]. Thermal gradients produce a combination of axial and flexural stresses and strains through the depth of the structure[6]. Although these stresses and strains are temporary in nature, their magnitude can exceed those resulting from live loads in certain cases. Therefore, thermal stresses and strains may result in thermal cracking. Thermal cracking does not generally affect the ultimate strength of the bridge components. However, the serviceability of the structure may be significantly affected because thermal cracking causes corrosion of reinforcing steel and thus reduces the service life of the structure[7].

The diurnal variation of air temperature and solar radiation leads to thermal gradients in a structure. Concrete expands and contracts when subject to temperature increase and decrease, respectively. During a sunny day, the exposed bridge deck heats up more quickly than the underside of the bridge since the underside is shaded from direct sunlight. As a result, a positive thermal gradient will occur[8]. The magnitude of this gradient depends on the amount of radiation absorbed by the deck. In the summer, the positive gradients are typically significant, ranging from 38 to 55 °F (21 to 31 °C), when the amount of solar radiation is at a maximum[8]. These gradients appear to be largest when longer periods of cooler ambient temperature are followed by the larger solar radiation days[9]. A bridge experiences a negative thermal gradient when the deck slab of the bridge subject to larger downward temperature swings than the underside of the bridge. Because the surface area of the bridge deck is typically much larger than the rest of the superstructure, the deck dissipates heat more rapidly than the bottom during the night. Peak negative thermal gradient tends to occur in the fall through spring when downward temperature cycles are largest. The negative thermal gradient magnitude is highly variable because it is dependent on the temperature distribution in the structure at the time when cooling begins and the difference between concrete and ambient temperatures[8.]

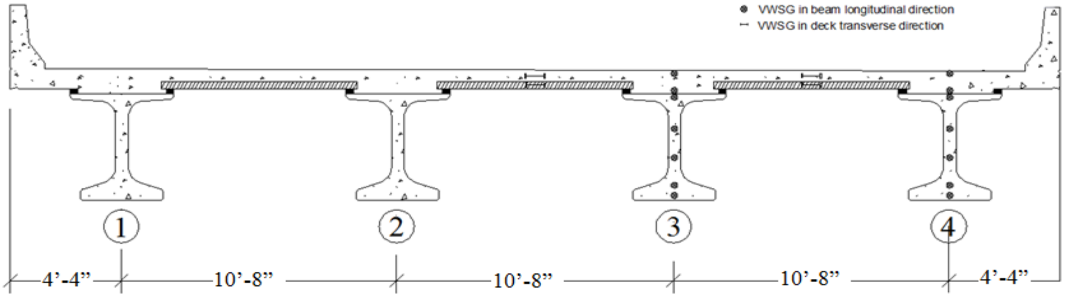
Myers and Yang studied the thermal behavior of high performance concrete bridge girders[7]. They found that the average maximum positive gradients were lowest during the winter months and highest during the summer months. Maximum daily negative gradients also varied from day to day. The time of the year did generally not affect negative gradients. They frequently occurred sometime during the early morning, but the exact time varied substantially from day to day. The average maximum negative gradients remained relatively constant during the year. The maximum positive gradient ranged from 23 to 36 °F (13 to 20 °C), and the peak negative gradients ranged from 7 to 20 °F (4 to 11 °C).

Gross in his Ph.D. study[9] traced the thermal gradients of four different bridges constructed with high performance concrete and high strength concrete in the State of Texas. Thermal gradients were measured for a one-year period. He found that the maximum bridge positive thermal gradients ranged from 28 to 36 °F (16 to 20 °C) for all four bridges. However, he found that negative thermal gradients ranged from 11 to 13 °F (6 to 7°C). Furthermore, he concluded that the design positive gradients suggested by NCHRP 267 and AASHTO LRFD underestimated the temperature measured at two depths of the deck. Otherwise, the shapes of the measured and design positive gradients were similar. The measured negative thermal gradients correlated very well with those predicted by NCHRP 267 and AASHTO LRFD.

BRIDGE DESCRIPTION

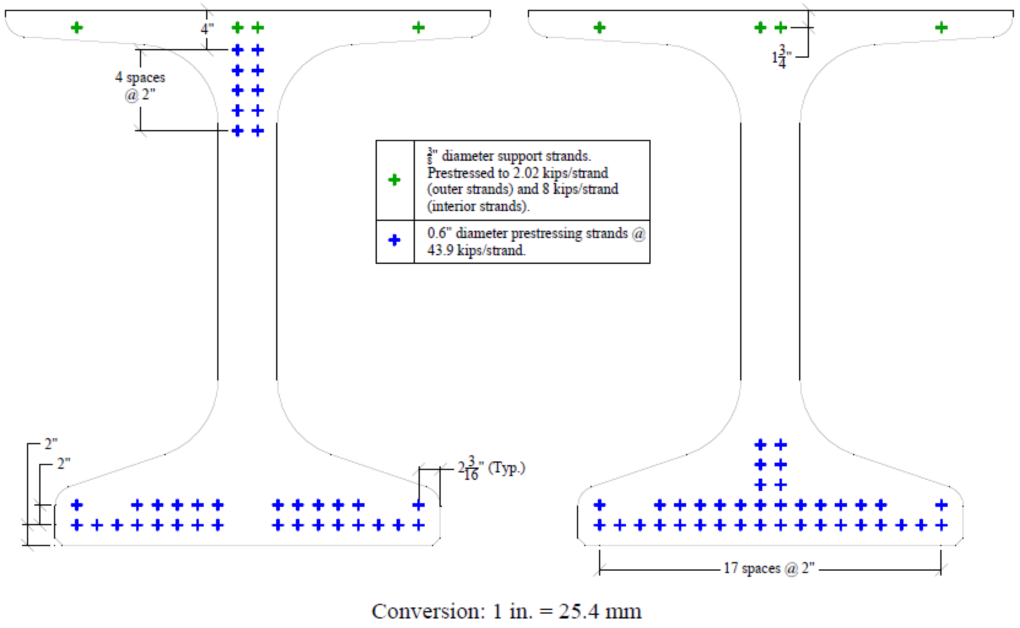
The A7957 Bridge on Highway 50 is located in Osage County, Missouri. The bridge has three spans with PC/PS concrete girders. The bridge was designed to be simply supported for dead load and continuous for live load via a CIP deck[11, 12]. Each span was designed with concrete mixtures of different compressive strength. The two exterior spans are 100 ft (30.5 m) long and one interior is 120 ft (36.6 m) long. The superstructure is supported by two intermediate bents and two abutments. The bridge has a superelevation of 2.0%.

Each span implemented four PC/PS Nebraska University 53 (NU53) girders as shown in Figure 1. The NU 53 girder was developed by the University of Nebraska's Center for Infrastructure Research in cooperation with the Nebraska Department of Roads. The girder's cross section provides several advantages during construction, giving designers more flexibility to increase strand capacity and reduce stress concentration in the edges by curved fillets (see Figure. 2). Span two with HS-SCC was utilized for this study. The beams were prestressed by 38, Grade 270 steel strands: 28 straight and 10 harped at double harping points. The 0.6 in. (15 mm) diameter strands were 7-wire, low-relaxation strands. Four additional 3/8 in. (9 mm) diameter prestressing strands were added within the top flange of each girder for crack control. The jacking force per strand was approximately 44 kips, slightly overstressed to 45 kips to compensate for chuck slippage losses.



Notes: 1 in. = 25.4 mm

Fig. 1 Bridge A7957 cross section



a) End view b) Mid-span view

Fig. 2 Cross section view of NU 53 girder

The target 28-day compressive strength of HS-SCC was 10,000 psi (68.9 MPa) and the specified release strength was 8,000 psi (55.2 MPa). The mixture proportion of HS-SCC mix design is presented in Table 1. Steam curing regime was utilized to accelerate the hydration process of all PC/PS girders. The maximum temperature of steam regime did not exceed 120 °F (49 °C). The precast girders and deck panels were fabricated in August 2013 at County Materials Corporation, located in Bonne Terre, Missouri, USA. Erection began in September 2013. The deck slab was cast from the east side to the west of the girder, after the erection of girders at the site in October 2013. The bridge entered into service (i.e., opened to traffic) during the middle of 2014 after the roadway was completed.

Table 1 HS-SCC mixture proportions

Type	Material	HS-SCC
Coarse Aggregate, (lb/yd^3)	(1/2”) Grade E Dolomite	1340
Fine Aggregate, (lb/yd^3)	Weber, Cristal City Sand/Class A Ledges 4-1	1433
Cement, (lb/yd^3)	Portland Cement – Type I	850
w/c	---	0.33
Chemical Admixtures, oz/yd^3	Air Entraining Agent	17.0
	Water Reducer and Retardant	76.5
	High Range Water Reducer	25.5
Design Air Content (%)	---	5

Notes: 1 lb/yd^3=0.593 kg/m^3, 1 oz. /yd^3=37 g/m^3

MONITORING SYSTEM

The structural monitoring system was installed on the bridge to measure strains and temperatures. This paper analyzes more than two years' worth of temperature data. The focus of the monitoring data analysis is on finding the maximum positive and negative temperature gradients that can develop in the bridge girders and comparing those to design code guidelines.

MEASURMENTS

Thermistors within VWSGs were utilized to monitor the temperature gradient within the cross section of the girders. Temperatures were recorded using an automated data acquisition system installed on the bridge. Since the bridge was not equipped with a weather station, temperature data from the closest weather station to the bridge monitored by the National Climatic Data Center (NCDC) via the internet was used[13]. The closest NCDC weather station is located at the Jefferson City Water Plant, MO, which was approximately 17 miles (27.4 km) from the A 7957 Bridge. The ambient temperature was used as an indicator to predict the occurrence of maximum and minimum thermal gradients during the analysis. The daily maximum and minimum ambient temperatures are illustrated in Figure 3. Image of the bridge during the summer is shown in Figure 4.

The HS-SCC girders produced for span 2 of the A7957 Bridge were instrumented to obtain data for the measured strain and temperature. Two instrumented girders (namely: S2-G3 and S2-G4) of span 2 were monitored. The VWSGs locations within instrumented PC/PS girders are illustrated in Figure 1.

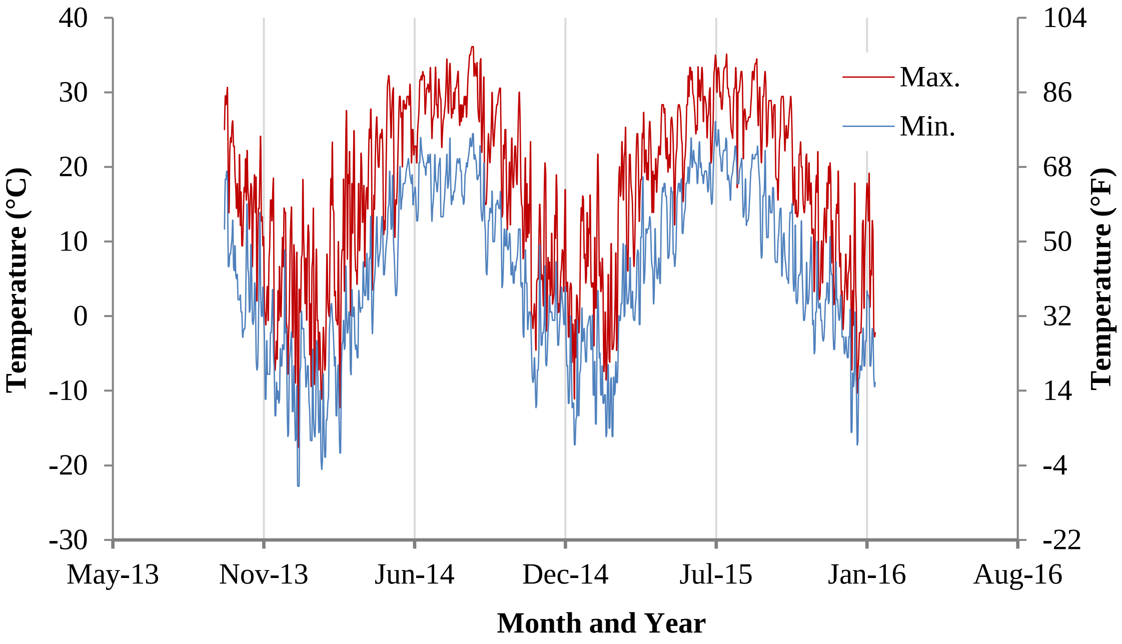


Fig. 3 The maximum and minimum ambient temperature

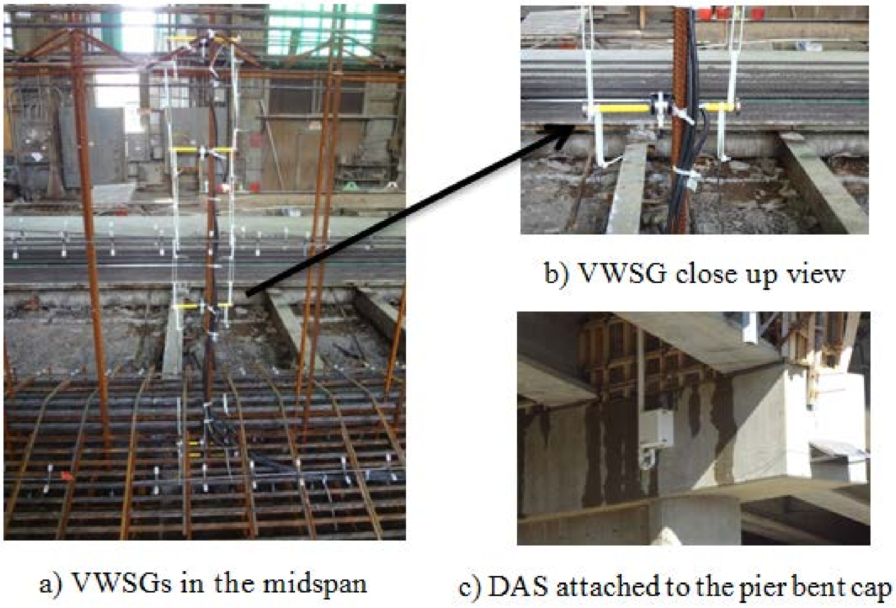
Fig. 4 Bridge A 7957 during the summer.

VIBRATING WIRE STRAIN GAUGES (VWSGS):

A total of 86 vibrating wire strain gauges with built-in thermistors (type EM-5) were utilized to measure the strain and temperature for the PC/PS girders. The VWSGs were installed in the mid-span and ends of the girder. The standard pattern in the mid-span consisted of five gauges over the height of the girder and two more in the slab above the girder. Images of the VWSGs within the girder's height are shown in Figure 5.

DATA ACQUISITION SYSTEM

The data from the VWSGs were recorded by a data acquisition system (DAS). The DAS used was Campbell Scientific CR800 box which works wirelessly. Following the erection of the girders, the CR800 DAS was anchored to the interior side of the intermediate bent pier caps for long-term monitoring. Data from these VWSGs was sampled at 5 mins intervals with the intention to measure static and slowly-varying response due to creep, shrinkage, and temperature variations. Communication with the DAS for data download was via a wireless modem over a cellular telephone network.



a) VWSGs in the midspan

b) VWSG close up view

c) DAS attached to the pier bent cap

Fig. 5 VWSGs installation

RESULTS AND DISCUSSION

During the day, the cross section of a concrete girder can heat or cool non-uniformly due to the low thermal conductivity of the concrete. This produces gradients that typically significant through the depth of the cross section. For purpose of computation, a positive thermal gradient was defined as a gradient in which the maximum temperature occurred at a location higher than the location of the minimum temperature. The maximum temperature typically occurs in the deck. Similarly, a negative gradient was defined as a gradient in which the maximum temperature occurs at a location lower than the minimum temperature in the deck. The magnitude of either gradient was defined as the difference between the maximum and the minimum temperatures through a cross section of a concrete girder. The positive thermal gradients are generally observed on hot, clear, and sunny afternoon with high solar radiation during the summer, typically between 2:00 and 4:00 pm. and negative thermal gradients occur in general between 1:00 and 8:00 pm during the cold, cloudy day throughout the year[15].

For NU girders, typical heating and cooling behaviors on sunny summer days and cloudy winter days are shown in Figure 6 through Figure 9, respectively. A positive gradient exists when the deck heats up quicker than the beam. During the morning (8:00 am) the deck warms up more quickly from solar radiation than the underside of the superstructure (beams) which is shaded from direct sunlight, resulting in a positive gradient. The magnitude of this gradient is increased during the afternoon (12:00 pm – 2:00 pm) where the beam heats up somewhat uniformly, however; since the surface area of the deck is typically much larger than the beams, the deck heats up at a faster rate than the beam. During the late afternoon and early evening, the temperature toward the top of the deck begins to drop quickly, as the deck reradiates heat to the atmosphere. The beam temperatures fall down slowly and uniformly until the deck temperature drops below the beam temperature and results in a negative gradient.

Figure 10 and Figure 11 illustrate the time of maximum daily positive thermal gradients and negative thermal gradients occurrence for interior and exterior HS-SCC girders, respectively. The magnitude of the maximum positive gradient varied substantially from day to day. Maximum positive gradients trended to be higher during summer months and lower during the winter months because of the intense solar radiation and high ambient temperature. The average maximum negative gradients are substantially smaller than the average maximum positive gradients. As visible in Figure 10 and Figure 11, thermal gradients in the interior (S2-G3) and exterior (S2-G4) girders had a slightly different distribution over the years. These differences can be attributed to the intensity of solar radiation on the top surface of the girders (deck slab). The interior girder was shadowed during the morning and the afternoon even though the solar attitude is the lowest during that time. In contrast, the exterior girder was exposed to direct sunlight on the south side from approximate sun rise to sun set because the deck overhang does not shade the beam surface. In other words, the differences were due to the shadow.

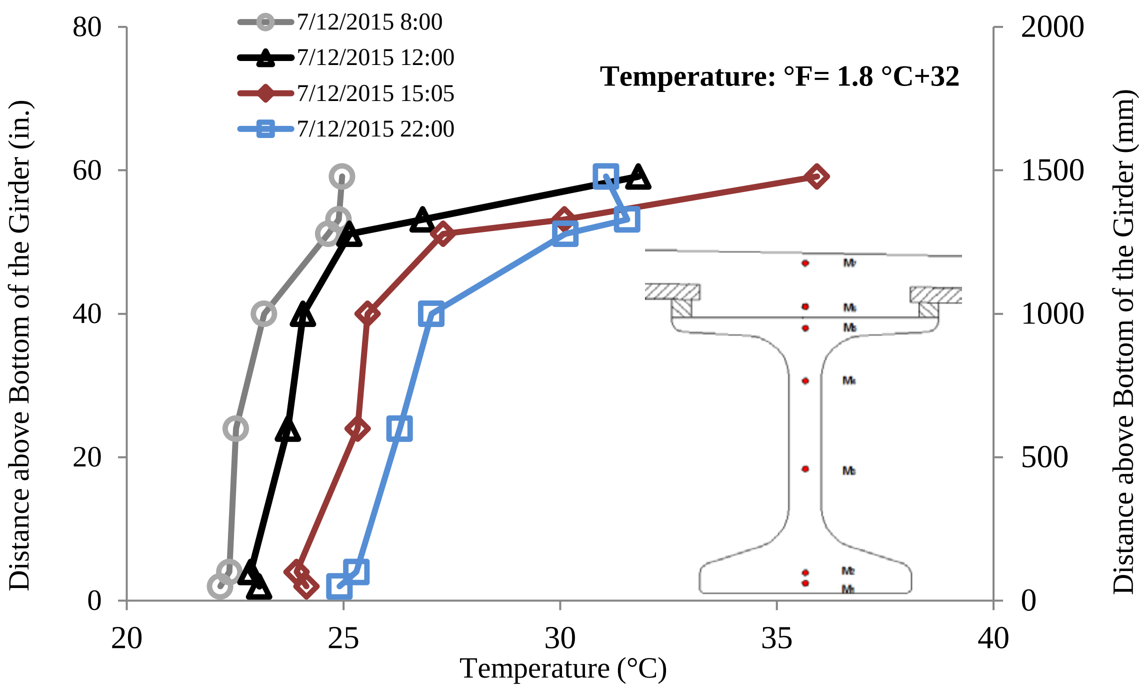


Fig. 6 Typical heating behavior in interior girder (S2-G3) on a sunny summer day

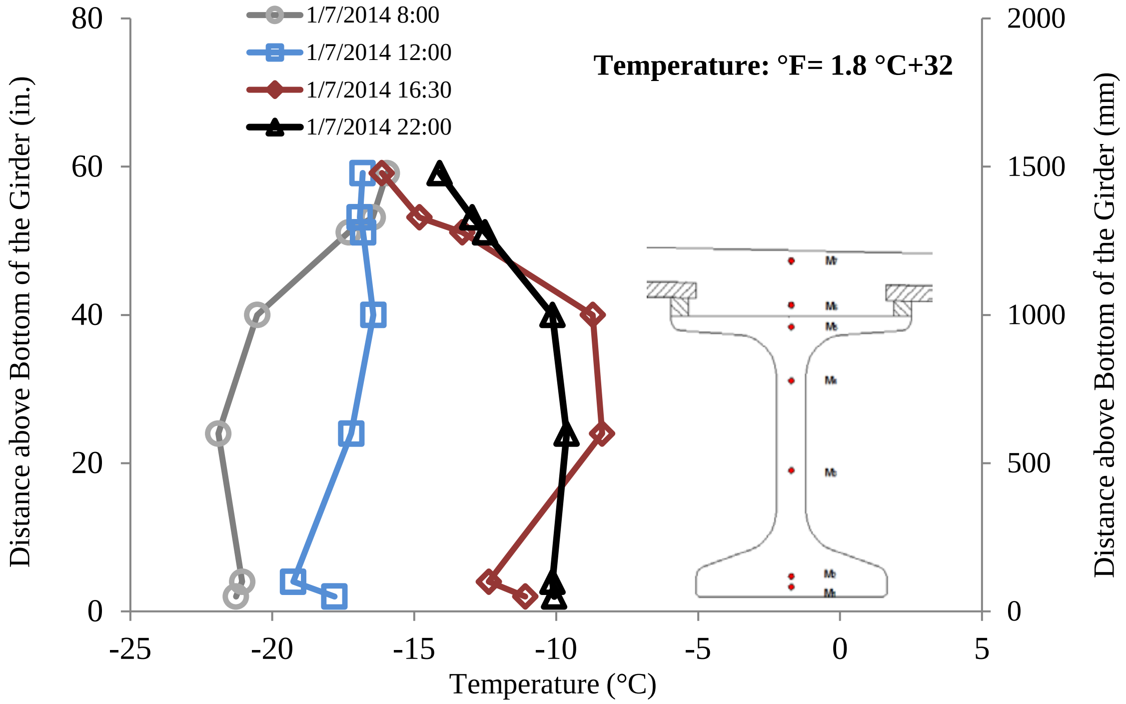


Fig. 7 Typical cooling behavior in interior girder (S2-G3) on a cloudy winter day

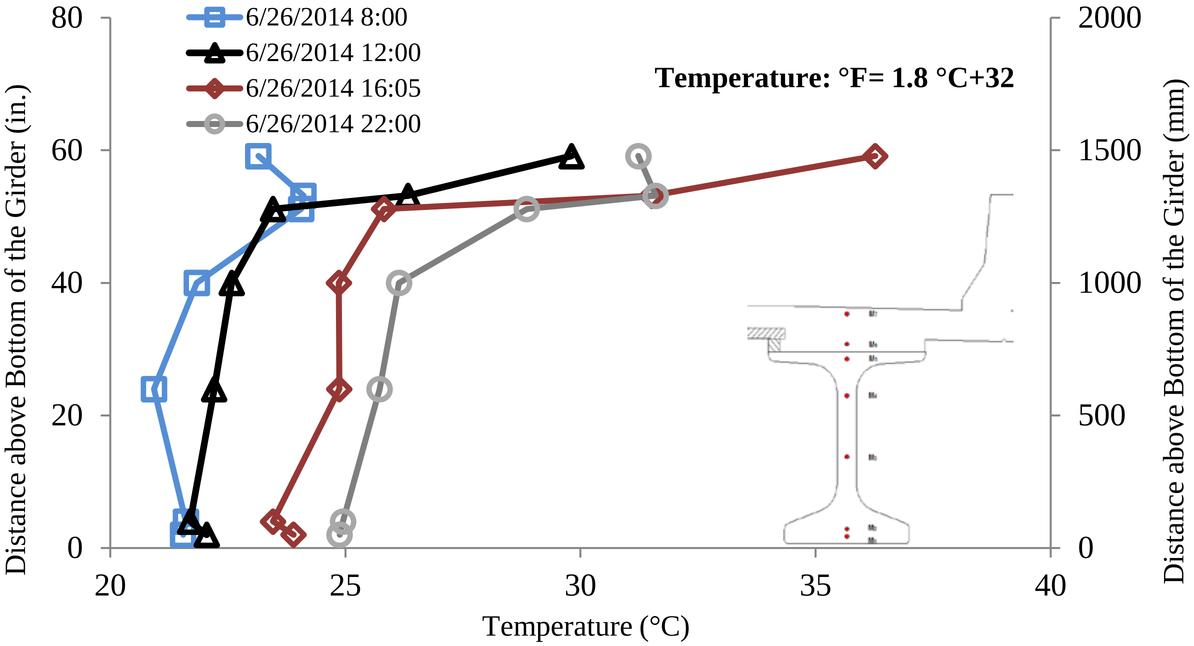


Fig. 8 Typical heating behavior in exterior girder (S2-G4) on a sunny summer day

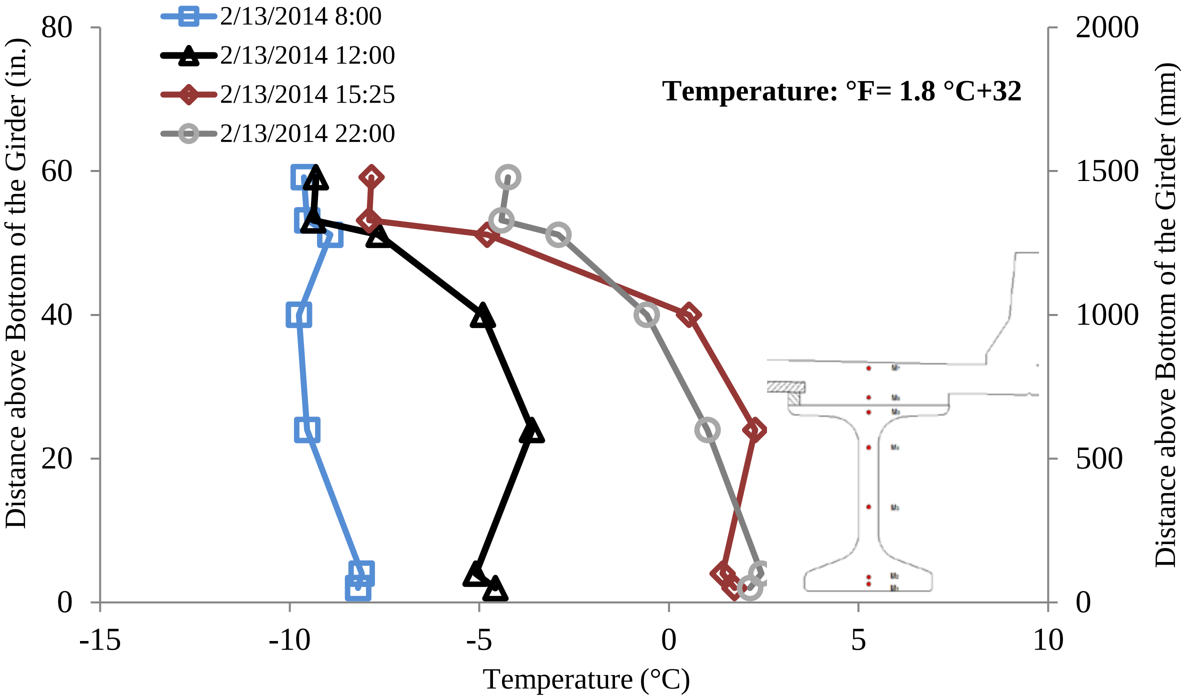


Fig. 9 Typical cooling behavior in exterior girder (S2-G4) on a cloudy winter day

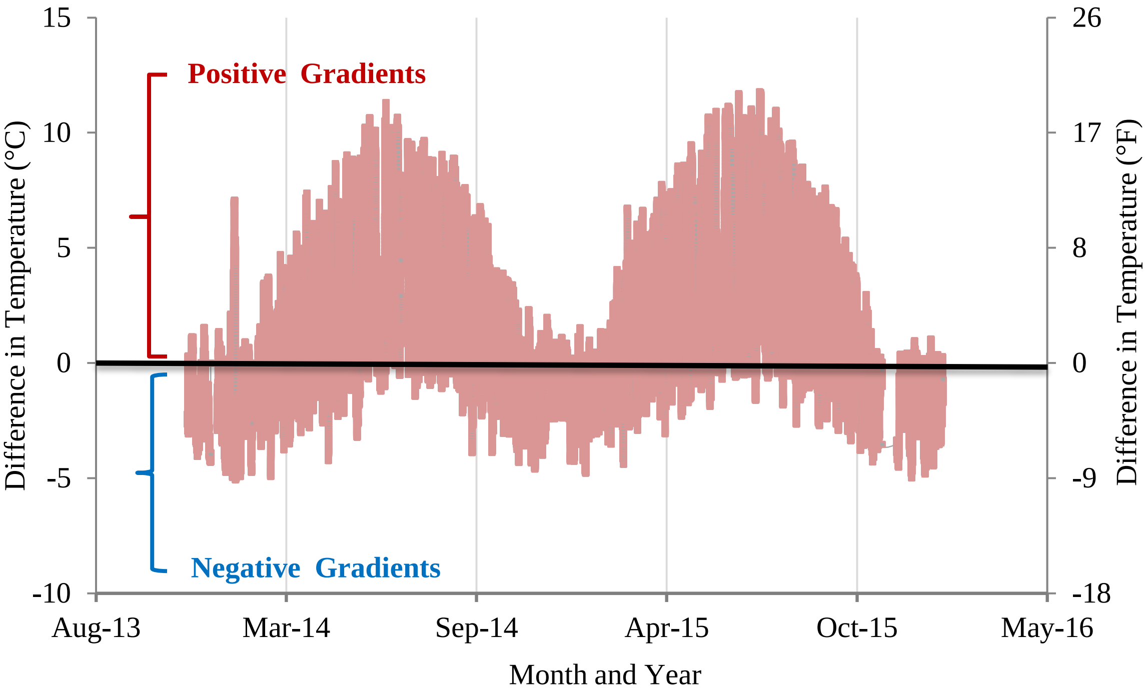


Fig. 10 Positive and negative daily thermal gradients of interior girder (S2-G3)

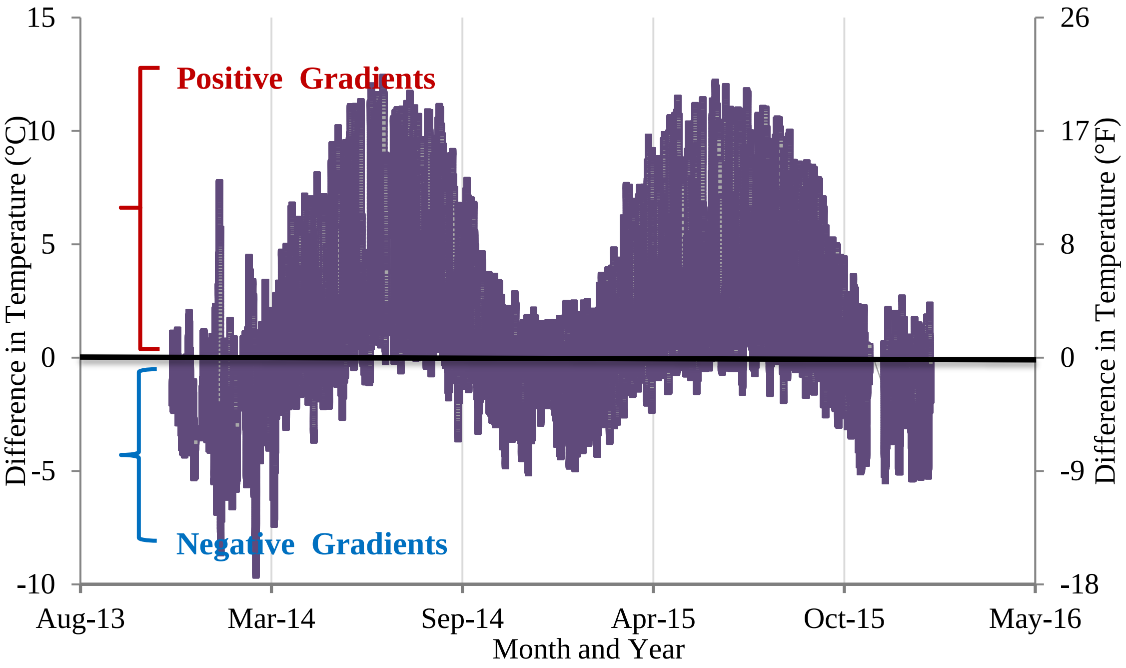


Fig. 11 Positive and negative daily thermal gradients of exterior girder (S2-G4)

Magnitudes of the maximum measured thermal gradients for exterior and interior HS-SCC girders are summarized in Table 2. The peak positive gradients recorded at a time during measurement period ranged from 21.2 to 25.77 °F (11.78 to 14.32 °C), and the peak negative gradients ranged from -9.09 to -17.23 °F (-5.05 to -9.57 °C). It is important to mention here that these gradients are temperature differences between the beam and the location of the top deck gauge [2 in. (50 mm) below the deck surface], not the deck surface.

The positive thermal gradients for the supports of interior girder tended to be 3 to 5 °F (2 to 3 °C) higher than the mid-span, and the negative gradients tended to be 4 to 7 °F (2 to 4 °C) lower than the mid-span. However, the variation of positive gradients for the supports of exterior girder was minimal, and the negative gradients tended to be 1 to 4 °F (0.6 to 2 °C) higher than the mid-span. Possible considerations for the mid-span having a higher gradient can be attributed to the location of support which causes the girders to experience quite different temperatures due to shadow and solar attitude[15]. Moreover, the addition of the interior bent and cast in place connection masses affect heat gain and loss. At this location, heat will enter and leave from the girder ends in a higher rate than the deck surface. This action will cause a higher thermal gradient section than sections where heat can enter and dissipate more freely at the girder ends and deck surface, such as at mid-span[16].

To determine the applicability of HS-SCC girders to a current design standard, the results for the typical positive thermal gradients and negative thermal gradients were compared with the NCHRP report 276[8] and AASHTO LRFD specification[17]. The NCHRP report 276 and the AASHTO LRFD specifications provide the engineer with temperature gradients over the depth of cross section to predict the vertical thermal behavior of a bridge. Figure 12 illustrates the theoretical positive gradient compared to the interior and exterior mid span girders. Figure 13 illustrates the theoretical negative gradient compared to the interior and exterior mid span girders. It can be clearly seen in Figure 12 that the maximum measured positive gradients are reasonably similar in shape to the design positive gradients specified by NCHRP and AASHTO. The main differences are that the temperatures at bottom gauge [located 6 in (150 mm)] below the deck surface and temperature in the beam web [located 20 in (1000 mm) or less] below the deck surface were both underestimated by the design gradients for all cases. The measured negative gradients had a shape approximately similar to the design negative gradients. The only clear differences are all temperatures in gauges located 40 in. (1000 mm) below the deck surface were underestimated by NCHRP and AASHTO specification. More in-depth results will appeal in a full journal article to discuss the impact of these temperature gradients on bridge behaviors and/or design.

Table 2 Maximum and minimum thermal gradients

Girder ID	Support (West)		Mid-span		Support (East)	
	S2-G3	S2-G4	S2-G3	S2-G4	S2-G3	S2-G4
Positive Gradient, °F (°C)	25.77 (14.32)	22.89 (12.72)	21.20 (11.78)	22.26 (12.37)	23.90 (13.28)	22.57 (12.54)
Negative Gradient, °F (°C)	-15.60 (-8.67)	-16.22 (-9.01)	-9.09 (-5.05)	-17.23 (-9.57)	-13.16 (-7.31)	-13.14 (-7.30)

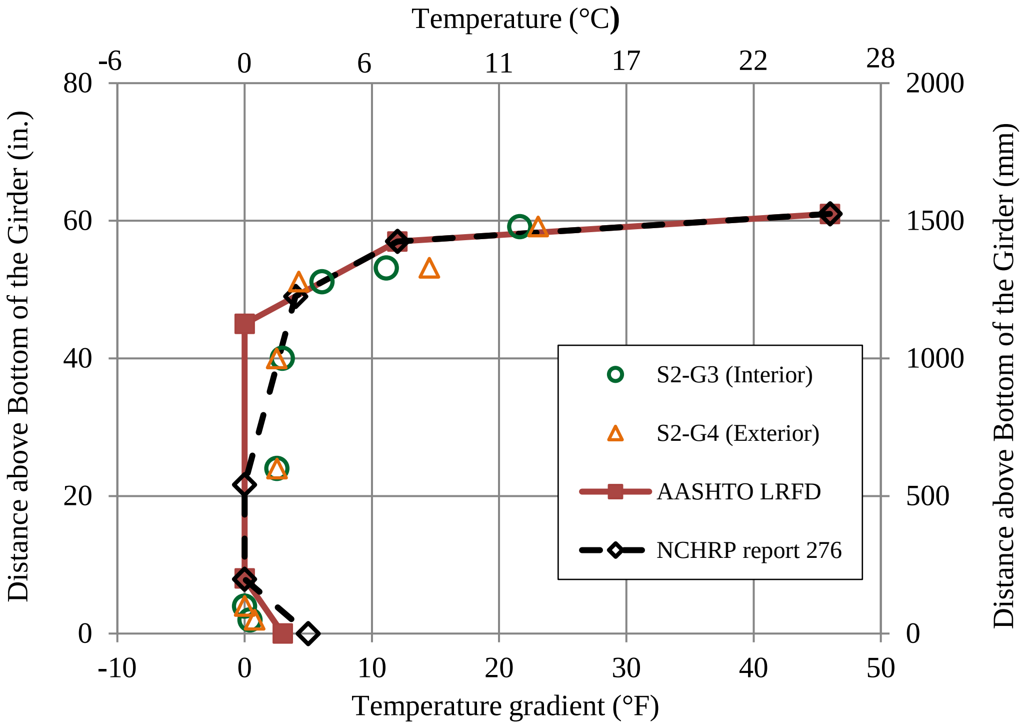


Fig. 12 Design positive gradients and maximum measured positive gradients

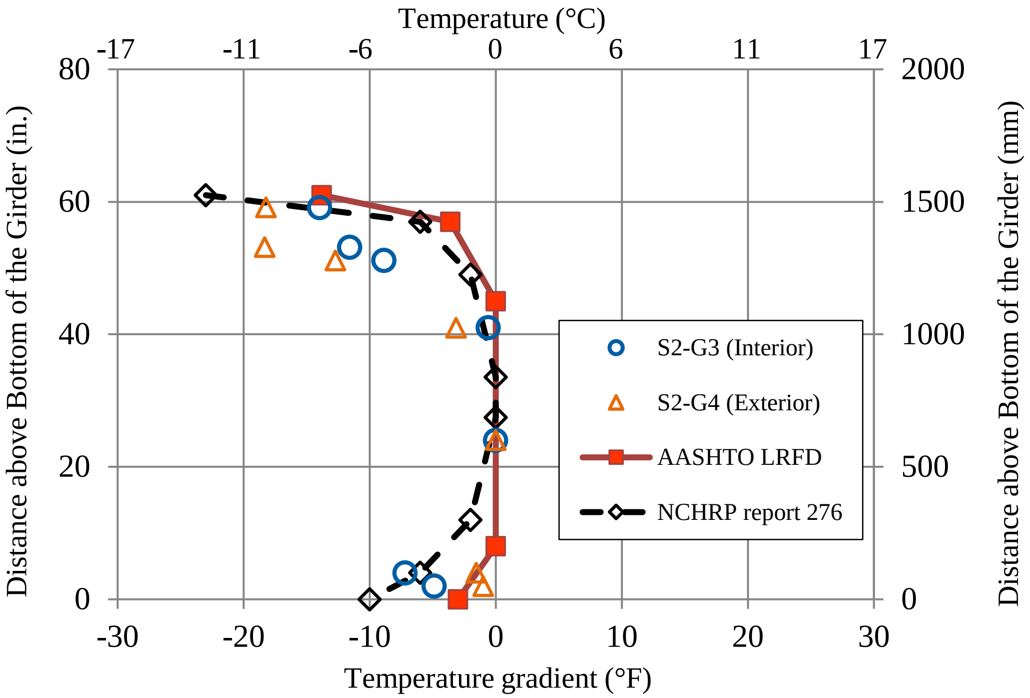


Fig. 13 Design negative gradients and maximum measured negative gradients

CONCLUSIONS

This study represents measured field-based thermal gradients of a new class of SCC PS/PC girders in the field. Thermal gradients were monitored for a two-and-a-half-year period in both girders. Maximum positive thermal gradients in the both girders ranged from 21.2 to 25.77 °F (11.78 to 14.32 °C). Maximum negative thermal gradients in the monitored girders ranged from -9.09 to -17.23 °F (-5.05 to -9.57 °C). These measured values are based on top deck gauges located 2 in. (50 mm) below the deck surface. The maximum positive thermal gradient typically occurred between 2:00 to 4:00 pm during the summer. However, the maximum negative thermal gradient typically occurred between 1:00 to 8:00 pm during the winter. The temperature profile of thermal gradient in exterior beams was observed to be quite different from those in interior beams under certain conditions. Differences in thermal gradients can be contributed to direct sun, shadow, and wind. The design positive thermal gradients suggested by NCHRP report 276 and AASHTO LRFD provided theoretical values that were close to the values of the top and the bottom of the beam. However, intermediate points appeared to be underestimated by the models. In both girders at 24 in (610 mm) from the bottom, there is a difference of 2.54 °F (1.41 °C) between measured data and theoretical ones. The design negative thermal gradients underestimated temperatures measured at certain depths within the beam.

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