

**UNIVERSITY OF GAZIANTEP
GRADUATE SCHOOL OF
NATURAL AND APPLIED SCIENCES**

**BEHAVIOR OF CONCRETE BOX-GIRDER BRIDGES EXPOSED TO
ENVIRONMENTAL THERMAL LOADS: EXPERIMENTAL AND FINITE
ELEMENT STUDY**

**Ph.D. THESIS
IN
CIVIL ENGINEERING**

**BY
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**Behavior of Concrete Box-Girder Bridges Exposed to Environmental Thermal
Loads: Experimental and Finite Element Study**

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In
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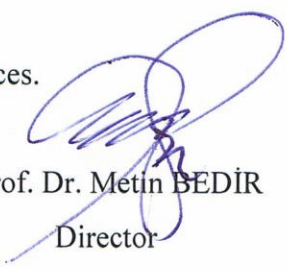
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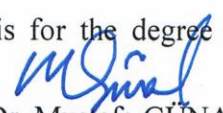
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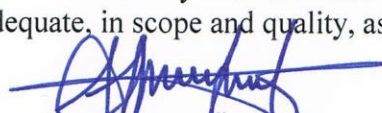
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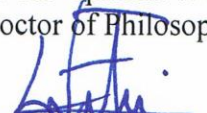
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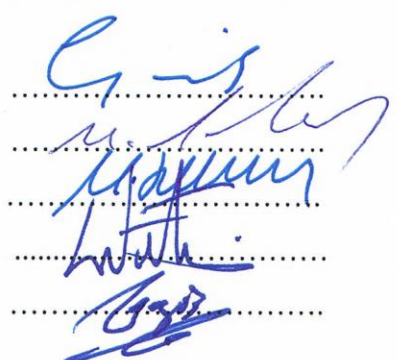
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Sallal R. ABID

ABSTRACT

BEHAVIOR OF CONCRETE BOX-GIRDER BRIDGES EXPOSED TO ENVIRONMENTAL THERMAL LOADS: EXPERIMENTAL AND FINITE ELEMENT STUDY

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Most of the worldwide available bridge design codes specify provisions to control the stresses that arise in bridge superstructures due to the effect of the diurnal and the seasonal environmental changes. Recently, most of the design codes provide ranges for the maximum change in the bridge mean temperature and models for temperature gradients. This research aims to investigate the effects of the environmental thermal loads on concrete bridges and to introduce special design recommendations for concrete bridges in Turkey. The research composed mainly of four parts. The first is the experimental work, in which a full-scale concrete box-girder bridge segment was constructed and instrumented with concrete temperature, air temperature, solar radiation, and wind speed sensors. In the second part, a heat transfer 3D finite element analysis was conducted to investigate the temperature distributions in concrete box-girders, which was verified using the experimental results and utilized to conduct detailed parametric studies. This finite element model was used in the third part with long-term weather records to introduce design provisions for thermal effects on concrete bridges. Finally, a thermo-mechanical finite element analysis was carried out to study the structural behavior of the concrete bridges under environmental thermal loads. The experimental results showed that the hydration heat has significant effects on temperature distributions during the early age of concrete, and that the temperature differs from one fiber to another along and across the different parts of the superstructure. The recorded maximum vertical and lateral temperature gradients for more than one-year measurements were approximately 20°C and 19°C, respectively. From the experimental records, equations were proposed to estimate the maximum vertical and lateral temperature gradients. Based on parametric studies, ANOVA showed that density and surface emissivity are of negligible effects, while surface absorptivity has much more effect on concrete temperatures and gradients. The experimental, statistical, and numerical studies of this research, in addition to long-term extreme weather data for different Turkish cities were utilized, from which mean temperature and temperature gradient models were proposed and design procedures were suggested for thermal actions in concrete bridges in Turkey.

Keywords: air temperature, concrete box-girder bridge, environmental thermal loads, solar radiation, temperature gradient.

ÖZET

ÇEVRESEL SICAKLIK YÜKLERİNE MARUZ KALAN BETONARME KUTUKİRİŞ KÖPRÜLERİN DAVRANIŞLARININ İNCELENMESİ: DENEYSEL VE SONLU ELEMANLAR ÇALIŞMALARI

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Dünya çapında mevcut köprü tasarım kodlarının çoğu, günlük ve mevsimsel çevresel değişikliklerin etkisiyle süper köprülerde ortaya çıkan gerilimleri kontrol etmek için hükümler bildirmektedirler. Son zamanlarda, tasarım kodlarının çoğu köprü ortalama sıcaklığındaki maksimum değişim oranları ve sıcaklık dağılımları için modeller önermektedirler. Bu araştırmanın amacı betonarme köprülerin üzerindeki çevresel sıcaklık yüklerinin etkilerini araştırmak ve Türkiye'deki betonarme köprüler için özel tasarım önerileri sunmaktır. Araştırma ağırlıklı olarak dört ana bölümden oluşmaktadır. İlk kısım tam ölçekli betonarme kutu kirişli köprü'nün inşa edilerek beton sıcaklığı, hava sıcaklığı, güneş radyasyonu ve rüzgâr hızı sensörlerinin yerleştirildiği deneysel bir çalışmadır. İkinci bölümde ise, betonarme kutu kiriş köprü'nün deneysel sonuçlarla doğrulanmış üç boyutlu sonlu elemanlar ısı transferi analizi yapılmıştır ve ayrıntılı parametrik çalışmalar için kullanılmıştır. Bu sonlu elemanlar modeli, uzun vadeli hava sıcaklığı kayıtları ile birlikte sıcaklığın betonarme köprülerin tasarım hükümlerine etkilerini araştırmak için üçüncü bölümde kullanılmıştır. Son olarak, çevresel ısı yükleri altında beton köprülerin yapısal davranışını incelemek amacıyla termo-mekanik sonlu elemanlar analizi gerçekleştirilmiştir. Deneysel sonuçlar betonun yeni döküldüğü dönemde hidrasyon ısısının sıcaklık dağılımları üzerinde önemli etkileri olduğunu ve bu sıcaklıkların köprü'nün farklı bölümlerinde çeşitli doğrultularda bir noktadan diğerine değiştiğini göstermektedir. Bir yıldan fazla süreyle kaydedilen en yüksek dikey ve yanal sıcaklık değişimleri sırasıyla yaklaşık 20°C ve 19°C'dir. Deneysel kayıtlardan, maksimum düşey ve yatay sıcaklık değişimlerini tahmin etmek için denklemler önerilmiştir. ANOVA parametrik çalışmalarına dayanarak, yüzey emiciliğinin beton sıcaklığı ve değişimi üzerinde çok daha etkili olduğunu gösterirken yoğunluk ve yüzey emisyonunun ihmal edilebilir oranda olduğunu göstermiştir. Bu araştırmanın deneysel istatistiksel ve sayısal çalışmaları, Meteorolojiden temin edilen Türkiye'deki farklı şehirler için uzun dönem aşırı hava verilerine ek olarak ortalama sıcaklık ve sıcaklık değişimleri modellemelerinde kullanılmıştır ve Türkiye'deki beton köprülerdeki ısı eylemleri için tasarım yöntemleri önerilmiştir.

Anahtar Kelimeler: hava sıcaklığı, beton kutu kiriş köprüler, çevresel ısı yükleri, güneş radyasyonu, sıcaklık dağılımı.

To

My parents, wife, and children

Ammar, Muammal, and Zainab

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LIST OF SYMBOLS

ρ	concrete density in kg/m^3
C_p	specific heat of concrete in $J/kg\ K$
k	thermal conductivity of concrete in $W/m\ K$
T	temperature at any time t
Q	rate of heat generated within the concrete body in W/m^3
n_x, n_y, n_z	direction cosines of an outwards vector normal to the boundary
q	total heat flux normal to the boundary in W/m^2
h_c	convection coefficient $W/m^2\ K$
T_s	surface temperature of the bridge
T_a	temperature of surrounding air
ϑ	velocity of the surrounding air (wind speed) in m/s
q_s	thermal solar radiation that absorbed by the exposed surfaces in W/m^2
a	absorptivity of the bridge surfaces
I_s	total solar radiation received by a horizontal surface
I_{bh}	the direct beam component of solar radiation on a horizontal surface
I_{dh}	the diffused component of solar radiation on a horizontal surface
I_{bn}	the direct beam component of solar radiation on an iclinded surface
I_{dn}	the diffused beam component of solar radiation on an iclinded surface
θ	the solar incidence angle (the angle between the sunrays and the normal of the surface)
β	the solar zenith angle (the angle between the directly overhead and the geometric center of the disk of the sun)
δ	the tilt angle of the surface with the horizontal plane
q_g	the component of the absorbed solar radiation reflected from the ground and the surrounding objects
I_g	reflected radiation flux from the ground and the surroundings
β_g	reflectivity of the ground and surrounding objects
q_m	the mutual irradiation between the surfaces of the box-girder
q_r	the long-wave radiation from the bridge surfaces and the surrounding atmosphere
ϵ	surface emissivity
β_s	Stefan-Boltzmann constant, which equals $5.67 \times 10^{-8} W/m^2 K^4$
$T(x, z)$	the temperature difference of a point with coordinates x and z
ϵ_T	the free thermal strain due to the temperature difference $T(x, z)$
α	the coefficient of thermal expansion of the concrete
ρ_z	the radius of curvature in the vertical z -direction at the centroid of the section
ρ_x	the radius of curvature in the transverse x -direction at the centroid of the section
σ_y	the total longitudinal thermal stress due to the temperature difference $T(x, z)$
E	the modulus of elasticity of concrete

ϵ_o the axial strain occurs at the center of gravity due to the temperature difference $T(x, z)$
 P the axial force occurs at the center of gravity due to the temperature difference $T(x, z)$
 M_z the bending moment about z-axis due to the temperature difference $T(x, z)$
 M_x the bending moment about x-axis due to the temperature difference $T(x, z)$
 I_z the moments of inertia of the cross section about z-axis
 I_x the moments of inertia of the cross section about x-axis

CHAPTER ONE

INTRODUCTION

1.1 General

Based on their functions and exposure types, concrete structures may carry different loading types during their design life span. Structures that are constructed in open environments, such as bridges, are continuously exposed to thermal loads from the surrounding environment. These thermal loads are caused mainly from the temperature of the ambient air, the solar radiation, and the speed of the wind, which are all fluctuated with time.

The diurnal and seasonal alterations of solar radiation and air temperature adversely influence the structural members of bridges and cause two main thermal actions. First, the average or mean temperature of the superstructure of the bridge fluctuates with time, resulting in longitudinal thermal movements (expansion or contraction) for simple span bridges, which differs from day to night and from season to season. If the bridge is restrained, the variation in the mean temperature causes thermal stresses. The second effect of the fluctuation of the ambient thermal loads is the causing of vertical and lateral temperature gradients between the subsequent fibers along the depth and the width of the superstructure and across the thickness of its different members. These temperature gradients are generally nonlinearly distributed along the height of the superstructure and the width of the slabs or the flanges. The nonlinearity of these gradients causes induced stresses. These stresses are called as self-equilibrating stresses, which arise to force linear thermal strains (to restrict the nonlinearity of strains), and to assure that the cross-section remains plane after deformation. The resulted stresses will of course lead to further deformations and may cause concrete cracking [1-5].

To control the thermal stresses and the deformations that arise from the continuous fluctuated effects of air temperature and solar radiation, design models for the vertical thermal gradients were suggested by many previous scholars. The nonlinear (fifth order) temperature gradient distribution suggested by Priestley in 1976 [6] is one of the earliest and most distinguished gradient models. This model is still recommended by the current New Zealand bridge design code [7] and the Australian bridge design code [8], but with different maximum surface temperature gradients. Another distinguished gradient model is the model proposed by Emerson in 1977 [9], which was recommended by the British bridge design code in 1978 [10]. Imbsen et al. [1] in USA suggested a tri-linear temperature gradient model in 1985. This model was first adopted by the AASHTO bridge standards in 1989 [11]. This temperature gradient model was later simplified to a bilinear one, which is continued depended by the current AASHTO provisions [12].

Other previous researchers [13-15] attempted to introduce simplified formulas to estimate the maximum temperature gradient on the top surface of the superstructure. This temperature gradient evaluates the maximum temperature difference between the hotter top exposed surface and the colder concrete core.

1.2 Temperature Gain and Loss

Bridges tolerate non ending fluctuated phases of heating and cooling because of the persistent contact with the ambient thermal loads that in turn result in cycles of temperature gain and loss. The values and distributions of the thermal loads differ from the cold season (winter) to the hot season (summer), and even for the moderate seasons (spring and autumn). In addition, they differ from one geographical location to another on the earth surface. These differences mainly arise from the differences in air temperatures and the different intensities and altitudes of sunrays. The geometry and orientation of the structure, the properties of the used materials, and the conditions of the exposed surfaces also play an important role on the fashion of temperature distribution through the different members of the bridge structure.

During the day hours of a sunny day, exterior surfaces, especially the top surface, absorb heat from solar radiation, which increases the temperature of these exposed surfaces. The heat absorbed at the top surface is conducted to the interior concrete

fibers crossing the thickness of the top slab. Similarly, the absorbed heat from other exterior surfaces is conducted to the interior surfaces of these members through the member's thickness, which increases the temperature of the interior layers. However, and within the early hours after the noon, the absorbed heat at the surfaces is not comparable (much larger) to that conducted to interior layers. Thus, the exterior surfaces become much hotter than the interiors, and hence causing a positive (heating) temperature gradient.

Because of the continuous heat conduction from the exposed surfaces during the day hours, the temperatures of the cores (interior layers) significantly increase and become the highest at times close to the sunset. During the sunset hours, solar radiation concentrates on the vertical surfaces by the low altitude-angle sunrays, while the top horizontal surface is being cooled. During the night hours, the cooling phase controls on all of the exterior surfaces. The cooling of the exterior hot surfaces takes place by two ways. The first is the heat convection from these surfaces to the ambient colder air, while the second is the thermal long-wave re-radiation from these hot surfaces back to the atmosphere. Both the convection and the re-radiation are related to the temperature difference between the surface and the ambient air. Due to the continuous cooling of the exterior surfaces by the cold air, their temperatures decrease significantly, especially before the sunrise. On the other hand, the interior layers keep hot in spite of the slow reversed heat conduction from the interiors to the exterior surfaces. Thus, the temperature gradient becomes negative (cooling), where the temperature of the surface is lower than the core temperatures.

If the concrete structure is cast in situ, an additional heat source is added to the environmental thermal sources, which is the heat that is produced internally in the material by the chemical reactions of the hydrated cement. This internal thermal load has a significant impact on concrete structures like bridges and slabs within the concrete's early age [16-20]. Because concrete is considered as a weak heat conductor, and due to the formwork sealing of most of the structure surfaces during the early days of the structure's life, the rate of heat dissipation by convection and re-radiation from the exposed surfaces is significantly slower than that of the heat production by cement hydration [21]. As a result, this unbalanced heat production and exchange leads to the concentration of the large amount of heat produced by the

cement hydration within the concrete interiors. Thus, the temperatures of the cores become much higher than that of the exterior surfaces, even during the hot day hours. It is believed that early age cracking of bridge structures can be due to the combined effect of cement hydration and the environmental thermal loads [22].

1.3 Research Objectives

In this research, experimental and numerical studies in addition to statistical analyses were conducted to investigate the heat exchange, the temperature and temperature gradient distributions, and the structural behavior of concrete box-girder bridges under the exposure to the fluctuation of air temperature and solar radiation. The research was directed to study in general the temperature distributions and the thermal behavior of concrete bridges under environmental thermal loads. Although, special concern was given to conduct localized thermal studies considering the weather history of Turkey. The aim of these studies is to provide practical design recommendations to overcome the thermal actions in concrete bridges in Turkey.

The current study was designed to attain many objectives. The main achieved objectives can be summarized by the followings:

1- In the experimental work of the current study, a reinforced concrete box-girder segment with full-scale dimensions was constructed and instrumented with many thermocouples to measure the concrete temperatures at different depths in the slabs and webs. In addition, a weather station composed of three sensors was installed to observe and record the environmental thermal loads, which are the air temperature, the solar radiation, and the wind speed. The data recording from the thermocouples and the weather station continued for more than a complete one-year cycle.

2- The enormous amount of data gained from the experimental work was utilized to conduct statistical regressions to estimate the maximum vertical and lateral temperature gradients based on the environmental records of air temperature, wind speed, and solar radiation. These statistical regressions led to practical formulas that can be used to evaluate the maximum vertical temperature gradient along the depth of the superstructure of concrete bridges, in addition to the maximum lateral temperature gradients along the width of the top and bottom slabs of concrete box-

girders. Moreover, simple formulas to estimate the average temperature of concrete bridges based on the air temperature data were introduced.

3- Using the finite element package COMSOL [23], the heat exchange in the experimental box-girder segment was modeled. All of the boundary thermal loads were applied, including the sun movement and solar radiation, the surface convection, the surface long-wave radiation, the reflected radiation from the ground, and the mutual radiation between the bridge surfaces. The temperature distributions were efficiently evaluated along and across the different parts of the box-girder and the model was competently verified using the experimental results. This heat transfer model was later used to conduct several geometrical and material parametric studies to evaluate the influence of these parameters on the temperature distributions in concrete box-girders.

4- Extensive database of weather history for several Turkish cities was utilized in numerical studies using the verified heat transfer finite element model to carry out extreme weather analyses. Many cities were selected to represent the seven Turkish regions (four coastal regions and three inland regions). The used data include hourly air temperature and solar radiation records for more than 50 years. The goal of the extreme analysis studies is to evaluate the temperature distributions and gradients in concrete bridges in the different regions of turkey, and to recommend special design consideration for these regions to overcome the thermal actions that can be evolved due to the environmental thermal loads.

5- A thermo-mechanical finite element model was conducted to investigate the structural behavior of the full-scale full-span box-girder bridge under the effects of thermal loads from air and sun. The structural and thermal boundary conditions were applied successfully. As a result, the deflections, the longitudinal movements, and the thermal induced stresses were calculated and studied for summer and winter conditions. The hourly variations of the deformations and the thermal stresses were extensively studied for different points and sections in the box-girder bridge.

1.4 Layout of the Thesis

This thesis composes of 11 chapters that cover the background of the problem, the experimental work and its results discussion, the numerical works, the parametric studies, the extreme analysis and design recommendations, and finally the conclusions.

After introducing a brief background about the problem in the first chapter, the history of the scientific research on the influences of air temperature, solar radiation, and the other environmental thermal loads on concrete bridges is introduced in chapter two. Moreover, the second chapter presents the extant literature of previous studies on concrete box-girder bridges, in addition to a review about the former and the current design provisions of thermal actions in some of the leading international bridge design codes.

Chapter three describes the experimental reinforced concrete box-girder segment and its construction, setup, and instrumentation. Details about the used sensors and data acquisition system are also provided in chapter three. On the other hand, the results of the experimental work are presented and discussed in chapter four. In this chapter, the time-dependent temperature variations at the different thermocouples are presented for several days from the different seasons. Chapter four also discusses the temperature distributions and gradients along the depth and the width of the box-girder at different time steps in different days from the year. The experimental temperature distributions during the early age of concrete are also presented and discussed in chapter four. Moreover, this chapter focuses on the experimental results of the mean temperature of the bridge and the temperature inside the box cavity for the whole test period.

In chapter five, the experimental test records of concrete temperatures, air temperature, solar radiation, and wind speed for the long test period are utilized to evaluate the individual and combined relationships between the environmental thermal loads and the maximum vertical and lateral temperature gradients. Linear, nonlinear, and stepwise regressions that resulted in simplified formulas with high degrees of confidence for the estimation of the maximum vertical gradients,

maximum lateral gradients, and mean temperature of the bridge are presented, discussed, and compared in chapter five.

Chapter six describes the COMSOL heat transfer finite element study, and the verification of the conducted thermal model with the experimental results, while in chapter seven, the verified COMSOL heat transfer model is used to conduct geometrical parametric studies. In chapter seven, the effects of the variation of six parameters on temperature distributions and gradients in concrete box-girder bridges are investigated. These parameters are the orientation of longitudinal axis of the bridge, the depth of the box-girder, the width of the cantilever portions of the top slab, in addition to the thicknesses of the top slab, the bottom slab, and the webs. On the other hand, the effects of the material thermal properties on the temperature distributions and gradients along the depth and the width of the box-girder are studied in details in chapter eight. Based on the results of the statistical ANOVA studies, the particular and combined effects of the changing of these properties are investigated in chapter eight.

In chapter nine, the COMSOL finite element model of chapter six in combination with long-term air temperature and solar radiation history, from 1960 to 2013, are used to study the extreme temperature gradients and mean bridge temperatures in concrete box girders in Turkey. The analyses are conducted for ten Turkish cities from the seven Turkish regions and for six months from the four seasons of the year. Suggestions and recommendations for the bridge design for thermal actions are introduced in this chapter.

In chapter ten, both the heat transfer field and the structural stress field are coupled in a finite element model using COMSOL finite element package. This chapter presents and discusses the time-dependent variation and the maximum values of the deformations that include the deflections and the longitudinal movements due to the environmental thermal loads under different weather conditions. The stress distributions along the different parts of the box-girder, in addition to the stress variation with time are also discussed in details in chapter ten. Finally, chapter eleven presents the most important findings and conclusions from the experimental study, the subsequent numerical studies, and the extreme analysis of Turkey.

CHAPTER TWO

LITERATURE REVIEW

2.1 General

Chapter two provides an overview about the effect of solar radiation and the ambient air temperature thermal loads on the structural behavior and the integrity of concrete bridges. The background of the problem is passed through briefly, while further details are given about studies concerned with concrete box-girder bridges. In addition, this chapter focuses on the earliest and the active provisions regarding thermal actions in concrete bridges in some of the international bridge design codes.

2.2 Temperature Effects

The problem of temperature effects on bridges has been focused on and became a required-study issue since Leonhardt et al. [24] in 1965 reported that detected cracks in a two-span box-girder bridge in Germany can be attributed to the nonlinear temperature variation along the depth of the superstructure. The authors reported that along one of the box webs, 5 mm width cracks were observed. Zichner [25] in 1981 addressed that cracks with widths of 0.2 to 0.4 mm were noticed along the bottom slab and the webs of many box-girder bridges. He reported that these cracks can be connected with, but not limited to, the temperature variations in the superstructure due to the environmental thermal loads. Other early reports about temperature-caused cracks and deformations of concrete box-girder bridges were summarized by Imbsen et al. [1].

Elbadry and Ghali [2] in 1986 disclosed that the thermal stresses that take place due to the effect of ambient thermal loads are comparable to those due to surface loads. They reported that near the bottom surface of a multi-span concrete box-girder bridge, thermal stress of about 2.8 MPa was produced due to the application of a

20°C nonlinear temperature gradient between the top and the bottom surfaces of the box-girder. On the other hand, for the same bridge, the service loads caused a stress of approximately 1.5 MPa only. Moreover, the authors showed that the predicted thermal stress in the transverse direction was 4 MPa. Priestley in 1976 [6] reported that transverse thermal tensile stresses of approximately 3.5 MPa can be arisen due to the effect of nonlinear thermal gradients.

Imbsen et al. [1] calculated the thermal stresses for many bridges in USA based on linear and nonlinear temperature gradients of many design codes. For a fifth order nonlinear temperature gradient of 30°C, the authors reported that the tensile thermal stress at the bottom fiber was about 3.1 MPa for a multi-cell box-girder bridge, while for single-cell box-girder bridges, the calculated maximum tensile stress at the bottom surface ranged approximately from 3.5 to 5 MPa.

2.3 Thermal Stresses

Ghali et al. [26] provided a satisfactory background about thermal stresses that occur due to temperature gradients caused by the variations of air temperature and solar radiation. This background is summarized in this section to understand the types and distributions of thermal stresses.

Figure 2.1(a) shows a simply supported beam subjected to linear temperature gradient along its depth. As shown in the figure, the linear temperature gradient causes linear free thermal strain. Thus, for this determinate beam, all fibers along the depth of the cross section will expand freely without any restraints that may cause stresses.

Figure 2.1(b) shows the same beam subjected to nonlinear temperature gradient. This nonlinear temperature gradient results in the nonlinear free strain distribution shown in the discrete line, which will try to deform the subsequent fibers along the depth nonlinearly. However, the resulting section after thermal deformation will not be plane. But according to the Navier's hypothesis, plane sections should remain plane after deformation. Hence, the actual deformation and thermal strain of the section will be plane. The difference between the free nonlinear thermal strain distribution and the actual linear strain distribution results in the restricting stress

distribution shown in Figure 2.1(b), which affects on the span direction and is termed as the self-equilibrating stress.

For indeterminate or continuous bridges, the thermal movements are not allowed freely at the supports. Thus, the thermal strains that result from linear or nonlinear temperature gradients will cause internal forces and end reactions. The produced internal forces and reactions result in another component of thermal longitudinal (along the span) stresses that are termed as continuity stresses.

In closed cross sections such as box-girders, the temperature variation along the depth of the box will cause transverse stresses along the top and bottom slabs and across the thickness of the webs in addition to the longitudinal stresses described above. These transverse stresses arise from the transverse internal forces that result from the continuity of the box section from webs to slabs, hence, from the restraining of the webs by the slabs and the restraining of the slabs by the webs. In addition, the transverse temperature gradient distributions along the slabs and across the thickness of the webs will also cause transverse stresses that are superposed to those result from the vertical temperature gradients.

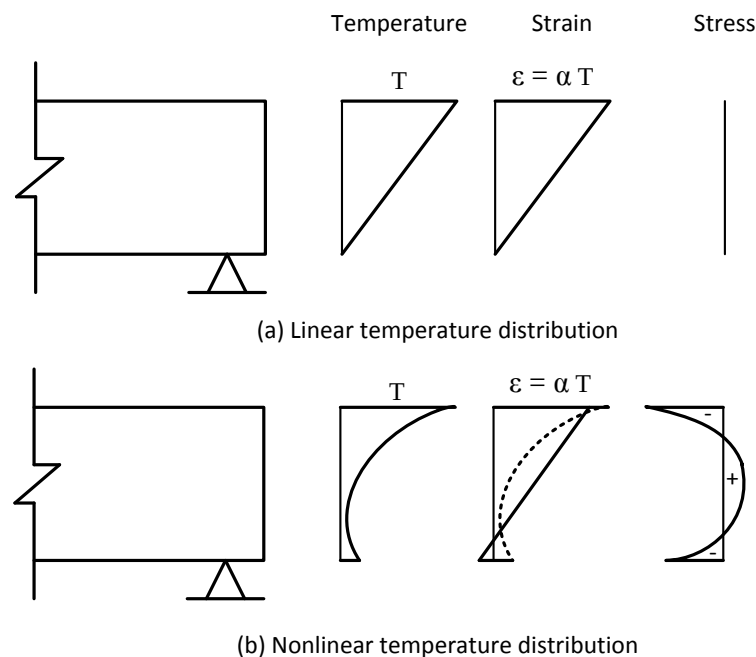


Figure 2.1 Stresses in a simply supported beam due to linear and nonlinear temperature gradients.

2.4 Early Studies

From 1955 to 1965, Narouka et al. [27], Barber [28], and Zuk [29] showed that nonlinear temperature gradients form in composite bridges and tried to introduce formulas to estimate the maximum temperature of the gradients in pavements, maximum surface temperature, and temperature difference between the top and bottom surfaces.

Based on the current literature survey, research carried out by Liu and Zuk in 1963 [30] and Wah and Kirksey in 1969 [31] were the earliest on concrete bridges. Liu and Zuk attempted to study the thermal behavior of prestressed concrete bridges with simple spans. They applied an analytical method introduced earlier by Zuk [32] to estimate the deflection, the thermal stresses, and the losses in prestressed forces due to linear temperature variation. Wah and Kirksey carried out field measurements and a theoretical study to evaluate temperature effects on reinforced concrete slab-beams simply supported bridge. They reported that a tensile stress of approximately 10 *MPa* was calculated from the measured strains.

Along the 20 years before 1990 several researchers carried out leading field studies to instrument concrete bridges with temperature and strain sensors. In 1968 [33] and later in 1982 [34], Emerson in England instrumented many types of bridges with temperature sensors to understand the temperature distributions and gradients in bridges under the effect of the ambient thermal loads. In 1979 in New Zealand, wood [35] conducted long term temperature measurements on several concrete bridges, which showed that temperature difference between the top and bottom surfaces of approximately 22°C can occur four times a year for a moderately shallow box-girders.

In 1984, Shiu [36] instrumented three concrete box-girder bridges with temperature and strain sensors, from which the observed maximum temperature difference was 11°C. One of these three bridges is the Kishwaukee River Bridge in Illinois, which was also instrumented by Potgieter and Gamble in 1989 [37] with 24 Carlsson strain gages. These strain gages were also provided with temperature sensors. Waldron et al. in 1990 [38] instrumented a concrete box-girder bridge in the United Kingdom with 60 thermocouples and several electrical resistance strain gages in addition to a

compact weather station. After 1990, several field studies were conducted worldwide to enrich the scientific knowledge about this subject.

During the 1970s, the 80s, and the 90s, many researchers conducted statistical analyses and numerical studies to understand the thermal behavior of concrete bridges. Among these researchers are Lanigan [39], Emerson [9, 40-44], Radolli and Green [45], Will et al. [46], Thepchatri et al. [47], Zichner [25], Elbadry and Ghali [2, 48], Imbsen et al. [1], Prakash Rao [49], Hirst and Dilger [50], Molessini and Massicotte [51], Mirambell and Aguado [52], Branco and Mendes [3], Saetta et al. [53].

To analyze the temperature distributions in concrete bridges and to evaluate their structural behavior, some of the aforementioned researchers developed or applied one-dimensional or two-dimensional numerical studies using the finite difference method or the finite element method. Langian [39] in 1973 developed a two-dimensional finite element heat flow model considering the temperature distribution is constant along the span. He verified this model with experimental data and found that the predicted temperatures agreed well with those from the experiments.

Emerson [9, 40] in England developed a one-dimensional heat flow model in concrete slabs using the finite difference method, in which the slab was divided to subsequent layers with specified thickness. In following studies [41, 44] and using field data from bridges instrumented with thermocouples, Emerson correlated the extreme effective temperature of bridges with the ambient air temperature. Radolli and Green [45] in 1975 developed a one-dimensional finite difference analysis similar to the one developed by Emerson.

Will et al. [46] in 1977 developed a two-step finite element numerical analysis program to estimate the temperature distributions in bridges and the resulted structural behavior. The developed program composed of two programs. The first was a time-dependent two-dimensional heat transfer program that evaluates the temperature distributions over the cross-section. However, in this program, the measured surface temperatures from three evaluated field studies were used as input data instead of using the environmental thermal loads. The second program analyzes

the three-dimensional structural behavior along the span, considering the temperature results from the first program as an input.

Thepchatri et al. [47] in 1977 used the program developed by Will et al. considering the time-dependent variation of air temperature, wind speed, and solar radiation. They studied three different bridges considering different extreme weather conditions for Texas and Austin. They reported that maximum compressive and tensile stresses of about 6.9 and 2.8 *MPa*, respectively, could be developed from such weather conditions.

In 1983, Elbadry and Ghali [48] developed a two-dimensional finite element program to analyze the heat conduction in bridge cross-sections of any shape and any materials. Edge fictitious elements were attached on the boundaries to model the boundary thermal loads. The program was termed as FETAB, which refers to the finite element thermal analysis of bridges. The authors in 1986 [2] used FETAB to study the vertical and transverse stress distributions in concrete bridges including the self equilibrating stresses, the continuity stresses, the total thermal and gravity loads stresses, and the transverse stresses in box-girder bridges. In addition, they studied the moment distributions and the cracking resulting from thermal stresses. They indicated that temperature due to ambient thermal loads distributes nonlinearly over the bridge cross-section and that it can cause serious stressing and cracking and therefore it should be considered in bridge design.

Hirst and Dilger [50] in 1989 made further development to the FETAB program to make it possible to include hourly measured data from weather stations. In 1993, Molessini and Massicotte [51] introduced the developed version FETAB2, which was capable to include more environmental parameters like clearness of the sky and the presence of snow for long test period of three years.

In 1985, Prakash Rao [49] attempted to solve the one-dimensional heat flow through the thickness of a multilayer slab using a series solution and the finite difference method. In 1990, Mirambell and Aguado [52] conducted many parametric studies using two-dimensional finite difference analyses to investigate the effect of the geometrical configuration of single and multi-cell concrete box-girder bridges. Branco and Mendes [3] in 1993 used two-dimensional finite element analyses to

study the nonlinear temperature distribution over the depth of the superstructure of concrete bridges.

Saetta et al. [53] in 1995 conducted a two-step finite element analysis to investigate the effect of environmental thermal loads on concrete box-girder bridges and concrete dams. The first step calculates for the temperature distribution by solving the heat conduction equation, considering all boundary thermal loads as one equivalent convection load, while in the second step, two-dimensional stress distributions are analyzed considering the temperature outputs from the first analysis as an input.

2.5 Earlier Temperature Gradient Models

According to a leading literature survey by Imbsen et al. [1], the leading gradient models before 1980 were introduced by Maher [54] in the United Kingdom, the Ministry of Work of New Zealand [55, 56], Priestley in New Zealand [6, 57], and Emerson [9] in the United Kingdom.

Maher in 1970 proposed a linear temperature difference of 18°C through the deck slab only, while considering a constant temperature along the rest depth of the superstructure. In 1970, the Ministry of Work of New Zealand recommended a constant temperature along the thickness of the deck slab, which was revised later to three nonlinear temperature variations, among which was a sixth degree nonlinear variation along the top 1.37 m of the bridge superstructures with a maximum top surface temperature difference of 30°C . In 1972, Priestley [57] suggested that a sixth degree temperature variation along the top 1.2 m of the superstructure with maximum top surface temperature of 32°C agrees better with the field temperature differences compared to that of the Ministry of Work.

In 1976, Priestley [6] suggested a revised nonlinear temperature gradient distribution to that suggested earlier in 1972. The suggested temperature gradient model composed of three parts. The first is a nonlinear fifth order variation along the top 1.2 m of the superstructure with maximum top surface temperature of 32°C . The second part is a linear variation across the top slab of box-girders over the box cell, which decreases from the top surface by 5°C per each 0.1 m of the slab's thickness.

On the other hand, the third part is a linear variation along the bottom 0.2 *m* of the superstructure with a maximum bottom surface temperature of 1.5°C.

Based on several field researches on several bridges in the United Kingdom, Emerson in 1977 [9] suggested that the linear temperature gradient recommended by the British Standards in 1972, is not adequate, and that the temperature variation is nonlinear. She introduced a temperature gradient model, in which the temperature distribution is nonlinear over the top 0.5 *m* with a maximum top surface temperature of 13.5°C. This gradient model was simplified by the British Standards BS5400 in 1978 [10] to a bi-linear temperature gradient above the top 0.4 *m* of the superstructure with top surface maximum temperature of 13.5°C, in addition to a linear temperature variation along the bottom 0.1 *m* of the soffit with maximum bottom surface temperature of 2.5°C.

In the earlier design practices of other European countries like Germany, France, Denmark, and Sweden, linear temperature variations were considered with maximum top surface temperature difference ranged from 5 to 15°C.

Before 1985, the USA AASHTO bridge design code did not specify any recommendations for temperature gradients along the depth of bridge superstructures. In 1985, Imbsen et al. [1] suggested a multi-linear temperature gradient that is composed of a tri-linear temperature variation along the top part and a linear temperature variation along the bottom part of the superstructure. The temperature at each part of this model depends on the location over the United States area. They introduced a tabulated comparison between many international design codes before 1985. Data from this table were summarized and reproduced in Table 2.1. However, countries like USA, Japan, Canada, and Italy, where no specifications for temperature gradients were available before that time, were excluded.

Table 2.1 Temperature actions in bridge design codes before 1985

Country	Maximum and Minimum Mean Temperatures °C	Vertical Positive Gradient °C	Vertical Negative Gradient °C
New Zealand	20, -20	Nonlinear 5th degree with maximum top surface temperature of 32°C (Priestley 1976)	None
United Kingdom	37, -14	Bilinear with maximum top surface temperature of 13.5°C	Two bilinear variations from the top and bottom surfaces
Germany	(10 to 20), -30	Linear between the top and bottom surfaces with 5°C difference	Linear between the top and bottom surfaces with -5°C difference
Australia	(40 to 50), (0 to -10)	Bilinear with maximum top surface temperature of 24°C	None
Sweden	Formula based on location and depth of the bridge's superstructure	Linear between the top and bottom surfaces with 10°C difference	Linear between the top and bottom surfaces with -5°C difference
Denmark	25, -15	Linear between the top and bottom surfaces with 15°C difference	Linear between the top and bottom surfaces with -10°C difference
France	30, -40	Linear between the top and bottom surfaces with 10°C difference	None

2.6 Thermal Considerations in Current Design Codes

Special thermal actions sections are included by the modern international codes of bridge design. The aim of the recommended provisions is to control the deformations and stresses arising from the effects of ambient air temperature and solar radiation.

The thermal actions provisions as defined by the design codes are classified mainly into two different categories. The first part gives recommendations for the possible variation of the bridge's mean temperature or effective temperature as defined by some codes. Thus, the highest and lowest mean temperatures to which the bridge should be designed to control the possible longitudinal thermal movements for simple span bridges and continuity reactions and stresses for indeterminate superstructures. On the other hand, the second part provides vertical temperature distributions along the depth of the superstructure to model the temperature gradient variation along this depth. This part is important to control the longitudinal self-equilibrating stresses that arise from the nonlinearity of the temperature gradient.

Some of the current bridge design codes gives guide lines or basic recommendation (but not gradient models) for the transverse temperature distributions along the width of the deck slab of the superstructure and the other lateral members (bottom slab or flanges of beams and other sections).

Among the currently available most widely used international bridge design codes are, the American AASHTO LRFD (American Association of State Highway and Transportation Officials) in 2012 [12], the British 5400-2 (British Standards) in 2006 [58], the European EN1991 (European Committee for Standardization) in 2009 [59], the Australian AS 5100.2 (Standards Australia) in 2004 [8], and the New Zealand's Bridge Manual (NZ Transport Agency) in 2013 [7]. In addition, many other nations have their own design codes and thermal actions specifications.

2.6.1 Mean Temperature Provisions

AASHTO [12] specifies two procedures to design for the bridge's uniform temperature, which is termed as the effective bridge temperature. The first procedure provides simplified tabulated values for the maximum and minimum mean temperatures depending on the type of the superstructure and the climate (moderate or cold). The maximum possible expansion and contraction should be calculated from the given temperatures based on the bridge temperature at the time of erection on supports. In the second procedure, AASHTO provides contour maps for the maximum and minimum design temperatures in USA based on the type of superstructure. The temperature range in this procedure to which the bridge should be designed for longitudinal thermal movements is the difference between the maximum and minimum design temperatures from the appropriate contour maps.

The European EN1991 [59] correlates the maximum and minimum design uniform bridge temperatures (mean temperatures) to the maximum and minimum shade air temperatures based on local isotherm maps for each country. The bridge should be designed for maximum expansion based on the maximum uniform bridge temperature and initial bridge temperature at the time of erection on supports. Similarly, to calculate the maximum design contraction, the minimum uniform bridge temperature should be subtracted from the initial bridge temperature. Similar

procedure is used by the British design code. However, the mean temperature of the bridge is termed as the effective bridge temperature.

The Australian AS 5100.2 [8] introduces tabulated values for the maximum and minimum shade air temperatures based on the region location and its type whether coastal or inland. Another table is introduced to determine the maximum and minimum average bridge temperatures from the shade air temperatures. The code specifies that for special or major structures, extreme values of the maximum and minimum shade air temperatures should be evaluated locally.

The New Zealand's Bridge Manual [7] allows for the use of an overall temperature change in the mean temperature of the superstructure, which is for concrete structures equals $\pm 20^\circ\text{C}$ for the calculations of the maximum expansion and contraction.

2.6.2 Vertical Temperature Gradient Provisions

In 1989, AASHTO [11] recommended the multi-linear temperature gradient distribution that was suggested by Imbsen et al. [1] and is shown in Figure 2.2(a) with three temperatures, T1 at the top surface, T2 at 0.1 *m* below the top surface, and T3 at 0.3 *m* below the top surface (note that this is not applicable for superstructures shallower than 0.4 *m*). The values of the temperatures T1, T2, and T3 were tabulated according to the location, where the area of the United States was divided into four zones based on the intensity of solar radiation. The temperature gradient is distributed linearly along the lower 0.2 *m* of the superstructure with a maximum temperature of 2.8°C at the bottom surface as shown in Figure 2.2(a)

The tri-linear gradient model was simplified later to the bilinear gradient model shown in Figure 2.2 (b), which is still used in the current AASHTO specifications [41]. The bilinear model consists of two temperatures. The maximum at the top surface (T1), followed by a linear decrease to the temperature gradient T2, which is located 0.1 *m* below the top surface. The gradient decreases from T2 to zero temperature at a depth of 0.4 *m* for most cases. The values of T1 and T2 are the same as those in the earlier tri-linear model for the four solar zones of USA.

For the case of the negative temperature gradient (cooling condition), AASHTO [12] specifies that the same gradient model shown in Figure 2.2(b) can be used after multiplication by -0.3 for concrete slabs and -0.2 for slabs with asphalt topping. Also the code permits to consider no temperature variation along the bottom part of the superstructure.

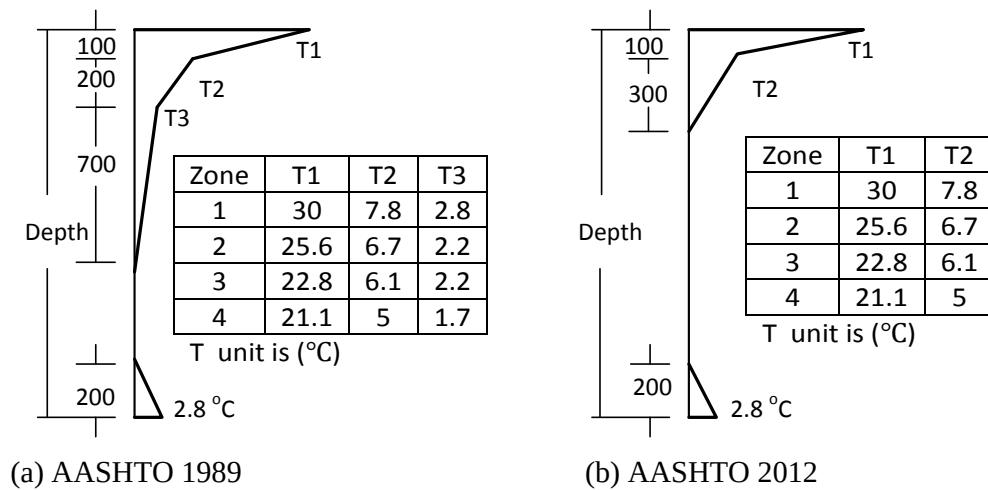


Figure 2.2 Vertical temperature gradient models of AASHTO.

The Eurocode EN1991 [59] introduces two different models for the vertical gradient. The first is a simplified one, which is an equivalent linear temperature variation between the top and bottom surfaces of the bridge deck. For concrete box-girders, the maximum positive (heating) and negative (cooling) temperature differences at the top surface are 10°C and -5°C, respectively, while for concrete beams and concrete slabs, the specified heating and cooling temperature differences are 15°C and -8°C, respectively. These values consider a 50 mm topping layer above the slab. For other topping cases, the given values should be multiplied by specified correction factors. For the case of unsurfaced girders, the given values should be multiplied by 0.8 and 1.1 for the cases of heating and cooling, respectively.

In the second approach, the EN1991 recommends the bilinear temperature gradient model of the British BS5400 [10, 58]. The temperature gradient models of the BS5400 and the EN1991 are shown in Figure 2.3 for both the heating (positive) and the cooling (negative) conditions. For the case of concrete box-girders without

topping layer and for sections deeper than 0.8 m, the values of T1, T2, and T3 of the heating case are 15.4, 4.5, and 2°C, respectively, while the values of T1, T2, T3, and T4 of the cooling case are -13.7, -1, -0.6, and -6.7°C, respectively.

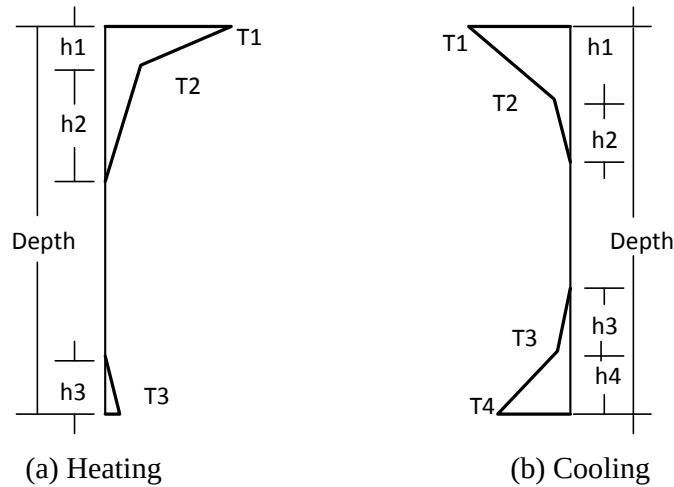


Figure 2.3 Temperature gradient models of concrete superstructures of BS5400 and EN1991 (a) heating and (b) cooling

As shown in Figure 2.4, for the positive temperature gradient, both the Australian AS 5100.2 [8] and New Zealand's Bridge Manual [7] recommend the Priestley's [6] fifth degree temperature gradient model. In this model, the temperature gradient extends to a zero temperature gradient along the top 1.2 m of the superstructure from a maximum temperature gradient at the top surface. However, the maximum temperature gradient at the top surface is different for the Australian and the New Zealand codes. The New Zealand's Bridge Manual specifies the same value recommended by Priestley, which is 32°C, while the Australian code recommends different values for the top surface temperature based on the region category, which ranges from 14 to 20°C. Note that the temperature above the box cavity is assumed to vary linearly across the top slab thickness in box-girder bridges for the two codes. However, the Australian code specifies that this temperature should equal the top slab maximum temperature plus 3°C for concrete box-girders.

For the case of negative temperature gradient, the Australian code recommends a linear temperature variation over the top 0.3 m of concrete superstructures, with a maximum top surface temperature of -0.4 times that of heating case. The New

Zealand recommends the using of the same Australian specifications for negative gradient case.

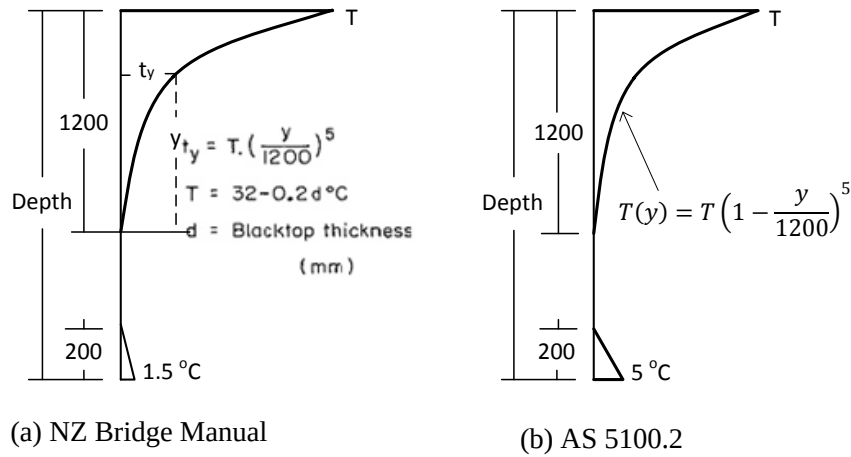


Figure 2.4 Temperature gradient models for concrete superstructures (a) the New Zealand Bridge Manual (b) the Australian AS 5001.2

2.7 Modern Studies on Box-Girders

Researches published after the year 2000 on concrete box-girder bridges are briefly reviewed in this section.

Roberts-Wollman et al. in 2002 [14] presented measured temperature data from a precast concrete box-girder bridge. These data were collected for 30 months period. The daily maximum and minimum temperature differences along the depth of the box section were discussed for the whole period. In addition, they were correlated to environmental thermal loads including air temperature, solar radiation, and wind speed from a weather station that is located 10 km away from the bridge site. From these correlations, formulas to predict the top surface maximum positive vertical gradient were introduced. In addition, the recorded maximum positive and negative temperature gradients were compared with the AASHTO design gradients.

Roeder in 2003 [60], presented that bridge movements are controlled by the weighted average temperature of the bridge cross section, where the minimum and maximum weighted temperatures occur in the early morning of the coldest day of winter and in mid-afternoon of the hottest summer day, respectively.

Pisani in 2004 [61], conducted a constitutive modeling numerical analysis and developed a computer program to analyze the structural behavior of compact cross-sections like reinforced or prestressed bridge deck slabs of box-girders or girder-system or roof slabs that are reinforced with any type of reinforcement. The considered loads were the service loads in addition to nonlinear thermal strains that result from nonlinear temperature distributions due to air temperature and solar radiation variation. The author concluded that the nonlinear temperature gradient markedly affected the stress distribution in the concrete section, especially at ultimate load. However, no significant effect was shown on the tensile stresses in the reinforcement.

In 2004, Li et al. [4] studied the thermal behavior of a long concrete box-girder bridge above ice-covered water in Canada. They investigated the hourly temperature of the concrete using thermocouples instrumented along three sections in the bridge. The depths of the instrumented sections were 4.5 m, 8.7 m, and 13.0 m. The concrete temperatures in addition to the air temperature, solar radiation, and wind speed were recorded for about two years. The obtained temperatures were divided into three components by taking the integrations of the temperatures over the area of the section. The first of these three components is the average temperature, which is the integration of the temperature over the area. The second is the linear temperature gradient, which is determined from the integration of the first moment of the area around the required axis divided by the moment of inertia about that axis. This component is calculated for both directions of the cross-section. The third is the nonlinear thermal component, which results in the self-equilibrating stresses. This component is calculated by subtracting the two other components from the nonlinear temperature distribution. The obtained vertical temperature gradient distributions were compared with the Canadian provisions CAN/CSA-S6-00 [62], which led to the conclusion that modifications should be applied for deep sections. The authors proposed a temperature gradient model for deep box-girders, which was termed as the Calgary Model.

In 2009, Chen et al. [16], carried out a field study on a prestressed concrete box-girder bridge in China to investigate the effect of the internal hydration heat and the external sunlight on the thermal behavior of concrete box-girder bridges. They found

that thermal stresses incurred by hydration heat might induce temperature cracks in prestressed concrete box-girder sections. By comparing the field results with the Chinese code [63], they found that the gradient model of this code is insufficient because it does not take into account the temperature gradient of the bottom slab.

Wang and Fang [64] in 2009 studied the temperature variation in concrete box-girder bridges. In their study, they conducted a two dimensional finite element analysis using the commercial program ANSYS and based on field measurements on a prestressed concrete box-girder bridge in China. They found that the finite element temperatures coincide with the measured ones within a maximum error of 3 °C.

Wang, et al. in 2010 [65] used in-site measurements and numerical analysis to investigate the temperature field in a continuous non prismatic box-girder bridge. The numerical analysis was conducted using ANSYS. The authors compared the predicted temperatures with the measured temperatures and found them agree well. They also compared the predicted stresses and deflections with those acquired from instrumented sensors and found good agreement between the measured and the predicted ones. In addition, they studied the effect of wind speed and considered it as a significant factor.

Larsson and Thelandersson in 2011 [66], carried out a finite element analysis using the finite element program BRIGADE/Plus to predict the varying thermal conditions in a concrete structure. They used the output daily temperature distribution variations for estimating extreme values for linear temperature differences based on climate data from meteorological stations. The analyses of extreme values with long term periods showed that the values for the positive linear temperature gradients in the Eurocodes are underestimated for the investigated conditions.

Song et al. in 2012 [5], investigated the characteristics of temperature gradients in high-performance concrete box-girder with unconventional cross-section. They compared the observed temperature gradients with Chinese [67], New Zealand, AASHTOO, and European standards. They found the temperature gradient models of these codes not appropriate for high-performance concrete box girders with unconventional cross section. They proposed a new method to determine the solar temperature action using the stationary binomial probability model of random

process.

Carboni and Lacarbonara in 2012 [68], attempted to model the dynamic behavior of concrete box-girder bridges under the effect of thermal loads from air temperature and solar radiation. A three-dimensional analysis was conducted using the COMSOL finite element commercial package. Using this model, the natural frequency of the bridge was studied, considering the variation of the environmental thermal loads. They showed that because of the change of temperature due to the thermal loads, the natural frequency changes during the day and from season to another. Due to the heating of the structure in summer, negative variations of the natural frequencies occurred, while due to the cooling of the structure in winter, positive variations were observed. They also showed that for simple span bridges in Rome, the predicted variation natural frequency changes by +3% to -2.5%. However, if the high friction forces at the supports can affect the free movement there, then the natural frequency may vary by up to 20%.

Gu et al. in 2014 [69] carried out field measurements and conducted a numerical study to evaluate the temperature distributions and the resulting self-equilibrating stresses in concrete-box girder bridges subjected to a steep drop of temperature due to a cold wave. The authors showed that a cold wave with short duration can cause serious unfavorable effects on large concrete box-girders. They compared the resulted vertical temperature gradients with gradient models of some existing design codes. The authors also proposed vertical and lateral temperature gradient models along the depth of the box-girder and across the thickness of its slabs and webs. In addition, they proposed what they called as a two-dimensional temperature gradient model to evaluate the compound effect of the vertical and lateral temperature gradients.

Nandan and Singh in 2014 [70] used environmental data recorded at North Carolina, USA to numerically investigate the influence of air temperature, wind speed, and solar radiation on the modal frequencies of concrete box-girder and T-beam bridges by conducting a two-steps finite element analysis. The results of the study showed that both the concrete temperatures and the modal frequencies were found to be changed daily and seasonally with the change of the environmental thermal loads.

CHAPTER THREE

THE EXPERIMENTAL WORK

3.1 General

In this study, an experimental work using a full-scale reinforced concrete box-girder segment was carried out to study the thermal behavior of concrete box-girders under combined thermal loading of solar radiation, ambient air temperature, and wind speed. The experimental measurements were started in May 2013 and finished in July 2014. The segment longitudinal axis was oriented to the east-west direction so that the vertical webs face the north and south directions.

3.2 Site Preparation

Before the construction of the bridge segment, a site of 13 *m* by 12 *m* was prepared for the experimental work at the campus of Gaziantep University (Latitude: 37° 2' 20" N and Longitude 37° 19' 2" E). The location was chosen so that it is near enough to the construction laboratory to facilitate the electric and water services, and at the same time far enough from surrounding buildings to avoid the shading effects.

The shadow length depends mainly on the sun position at the required time and the height of the shading building with respect to the experimental segment. The position of the sun plays an important role on the received incident intensity and distribution of solar radiation on the surfaces of the bridge segment. This position for a specific point on the earth surface differs yearly from season to season and daily from hour to another.

In summer, the sun moves to the south of the zenith except during the early morning hours and the late afternoon hours where the solar radiation intensity is lower than during the midday hours. On the other hand, sun rises from the southeast and sets at

the southwest in winter, which means that it moves to the south of the zenith during the full day hours. Hence, it can be concluded that shadow from the surrounding buildings and structures should be avoided from the south direction in addition to the east and west, while north direction has only minimal shading effects.

The distance between the nearest building from south and the bridge segment was more than 100 *m*, and from west it was about 35 *m*, while from east direction there was at least 150 *m* from the nearest building. On the other hand, shadow lengths were calculated [71] for the four seasons considering the effective solar shining hours between 8:00 AM and 4:00 PM as shown in Figure 3.1.

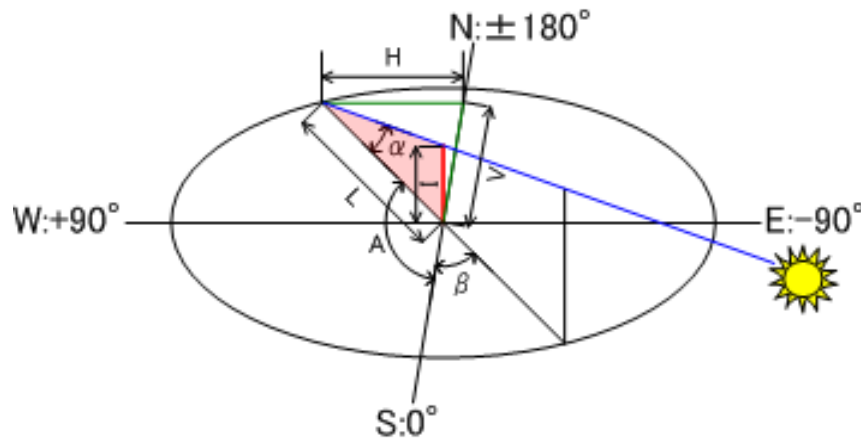


Figure 3.1 Shadow lengths for a building with height *I* [71].

The height of the nearest building from west is about 10 *m*, while the height of the experimental bridge segment surfaces ranged from 2.1 *m* to 4.5 *m*. It was found that the maximum effective shadow length between 8:00 AM and 4:00 PM was less than the distance between the surrounding buildings and the experimental box-girder segment during spring, summer, and autumn. The maximum shadow lengths *L* were 15.8 *m*, 9.0 *m*, and 19.0 *m* in 21-March, 21-June, and 23-September, respectively, which were less than the all distances from the surrounding buildings. Thus, it can be said that there was no shading problems during these days. During the late shining hours in winter, the sun becomes too low in the sky at the southwest direction and hence the shadow length becomes longer than in other seasons. The shadow length becomes about 27 *m* at 3:00 PM, which still less than the 35 *m*,

while at 3:30 PM, the shadow covers the supporting frame of the bridge segment with a total length of about 45 m. However, this has a negligible effect on the heat transfer analysis of the bridge segment, since after 3:30 PM the solar radiation intensity becomes too low in winter.

3.3 The Box-Girder Segment

A full-scale reinforced concrete box-girder segment was constructed to study the effect of the environmental thermal loads including solar radiation, ambient air temperature, and wind speed on the thermal behavior of concrete box-girder bridges. The segment width was 7.25 m at the top slab and 4.75 m at the bottom slab, while the length of the overhanging portions of the top slab was 1.25 m. The thickness of the top and bottom slabs including the overhanging portions was 0.2 m. The webs were vertical with an overall height of 2.4 m, while their thickness was 0.25 m. The length of the box-girder segment was 2.1 m. Figure 3.2 shows the detailed dimensions of the cross-section of the experimental box-girder segment.

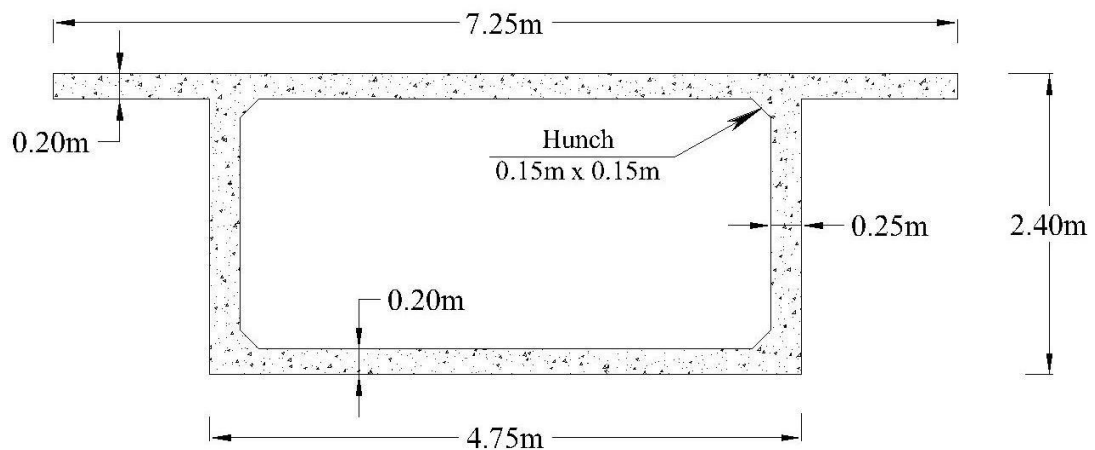


Figure 3.2 Cross-sectional dimensions of the experimental reinforced concrete box-girder segment

The bridge segment was constructed on a supporting reinforced concrete frame composed of four columns and two lateral beams. This frame was constructed to raise the box-girder from the ground to simulate the actual loading of the ground reflected radiation. Moreover, this supporting frame allows free fluent of air to the

lower surface of the bottom slab, hence, simulating the actual convection loading on the lower surface of the bottom slab. Figure 3.3 shows the form-working of box-girder segment on the reinforced concrete supporting frame after the full removal of the frame's formwork. Similar to the actual case, the supporting frame was thermally isolated from the box-girder. To assure that the supporting frame would not contribute the heat transfer process of the box-girder, contact between the two surfaces was prevented. Two layers of plywood were used on the top of the frame before the reinforcing of the box-girder segment as shown in Figure 3.4.

After the curing period, an insulation boards were used to seal the cross-section of the box-girder to satisfy complete thermal isolation through the span direction. The isolation material was a sandwich panel composed of two outer layers of glass fibrous reinforcement and an interior thicker layer of a gypsum board with a total thickness of 12.5 mm . The outer faces of the isolation boards were then plastered by 3 mm of an epoxy water proof finishing coat. This isolation is important to simulate the actual situation in box-girder bridges where no air or light flows inside the box. Figure 3.5 shows the isolation boards after installation, while Figure 3.6 shows the final view of box-girder after the plastering of the isolation boards with the final epoxy cementations layer.



Figure 3.3 Formwork of the box-girder segment on the supporting frame



Figure 3.4 Two layers of plywood on the top of concrete beams to thermally isolate the beams from the box-girder bottom slab



Figure 3.5 Installation of the isolation boards

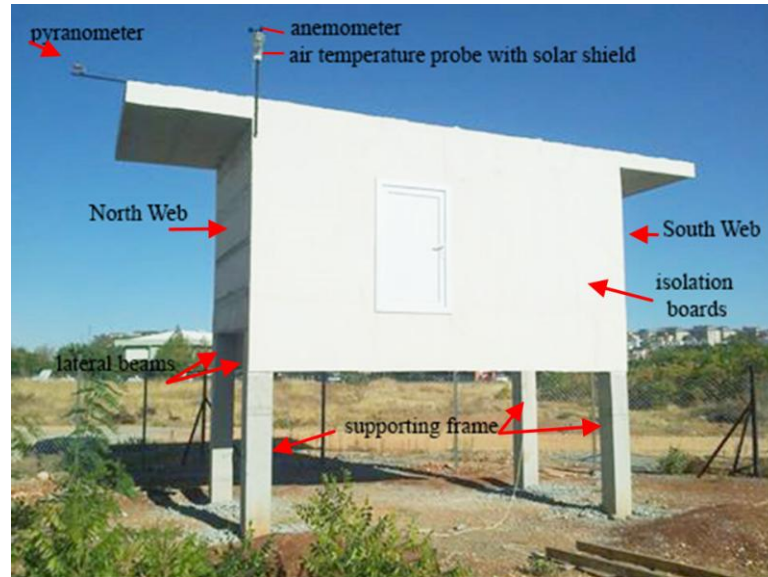


Figure 3.6 Final view of the box-girder

3.4 Instruments and Data Acquisition System

In this section, all sensors and measurement units are explained in details. The installed sensors include thermocouples, air temperature probe, wind speed anemometer, and solar radiation pyranometer. The measurement units on the other hand, include the data logger and the attached accessories.

3.4.1 Thermocouples

A thermocouple is a sensor to measure temperature. Any thermocouple composed of two dissimilar metals, which are joined at one end. As the temperature of the junction of the two metals is changed a voltage is produced, which can be correlated to a temperature reading. Thermocouples are commonly available as wire and in different combinations of metals and calibrations. The four most common thermocouple calibrations are J, K, T and E. Each of which has a different properties.

In this study, type T thermocouples were used to measure temperature in concrete during concrete pouring and during the whole period of testing. Type T thermocouples are made with a copper (positive) and a constantan (negative). The general temperature range of type T is -200 to 300°C , however, this range is also

affected by the wire diameter, which may be reduced as the wire diameter decreases. Type T was chosen because of its higher accuracy compared to the other types of thermocouples. As shown in Table 3.1, the estimated error of type T thermocouple is about 0.5°C, while for K, J and E types, the error is about 1.5°C, which is three times that of type T. The other types of thermocouples can work in higher temperature ranges as shown in Table 3.1, while such ranges are not applicable in the current research and thus type T is the best thermocouple choice.

The used thermocouples were ordered with special limits of errors and with thermocouple diameter of 0.25 mm (Gage No. 30) to further limit the possible error in temperature measuring. Figure 3.7 shows a picture of the used thermocouples.

Table 3.1 Comparison between the most common thermocouple types

Type	Temperature range °C (continuous)	Tolerance class one (°C)
K	0 to +1100	± 1.5 between -40 °C and 375 °C $\pm 0.004 \times T$ between 375 °C and 1000 °C
J	0 to +750	± 1.5 between -40 °C and 375 °C $\pm 0.004 \times T$ between 375 °C and 750 °C
E	0 to +800	± 1.5 between -40 °C and 375 °C $\pm 0.004 \times T$ between 375 °C and 800 °C
T	-200 to $+300$	± 0.5 between -40 °C and 125 °C $\pm 0.004 \times T$ between 125 °C and 350 °C



Figure 3.7 The used type T thermocouples

3.4.2 Air Temperature Probe

The 108 Campbell Scientific air temperature probe was used to monitor the ambient air temperature in the study field. The 108-temperature probe uses a thermistor to measure temperature. The probe was designed for measuring air, soil, and water temperatures. For air temperature, a radiation shield is used to mount the 108 probe and limit solar radiation effect as shown in Figure 3.8. The 108 probe works in temperature range of -50 °C to 100 °C with high accuracy measurements, the estimated error in temperature is 0.1 °C in temperature range of 0 °C to 70 °C, which is the normal temperature range. While in the worst case, this error may increase up to 0.35 °C, which is also fair enough. Table 3.2 shows the range of temperature errors of the 108 probe.

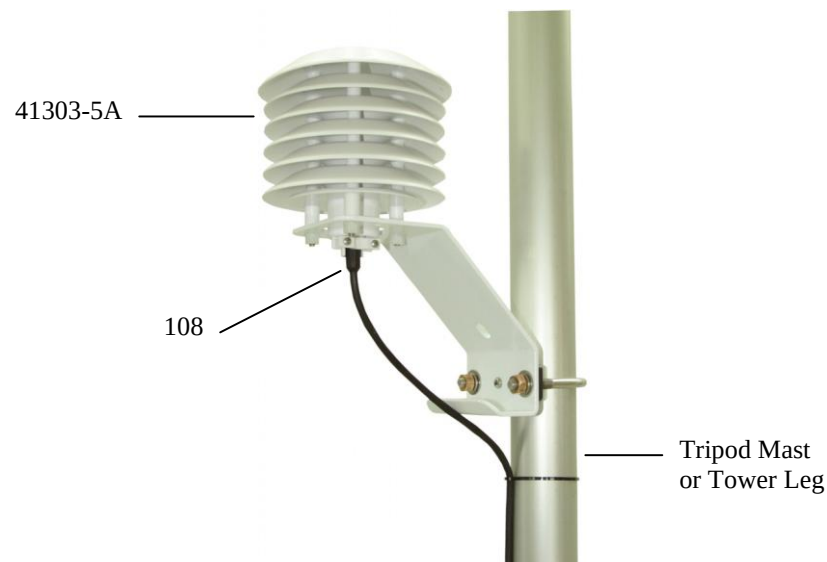


Figure 3.8 The 108 air temperature probe with solar shield

Table 3.2 The estimated temperature errors

Temperature Range °C	Temperature Tolerance ($\pm^{\circ}\text{C}$)
-5	0.14
0 to +70	0.10
+85	0.25
+95	0.35

3.4.3 Wind Speed Sensor

The three-cup NRG#40 anemometer, which is recommended by Campbell Scientifics, was used in this study to measure the wind speed. The sensor measuring range is from 0 m/s to 96 m/s . The used three-cup anemometer has high accuracy where the maximum estimated error is $\pm 0.14 m/s$ at 10 m/s . Figure 3.9 shows the used NRG#40 anemometer.



Figure 3.9 The NRG#40 three-cup anemometer

3.4.4 Solar Radiation Sensor

In this study, the CS3 apogee silicon pyranometer provided by Campbell Scientific is used to monitor the global sun plus sky radiation in the experimental field. Figure 3.10 shows the CS3 pyranometer. The CS3 measures a radiation range of 0 to 2000 W/m^2 with an accuracy of $\pm 5\%$ for daily total radiation and has a dome-shaped head to prevent water from accumulating around its head.



Figure 3.10 The CS3 apogee silicon pyranometer

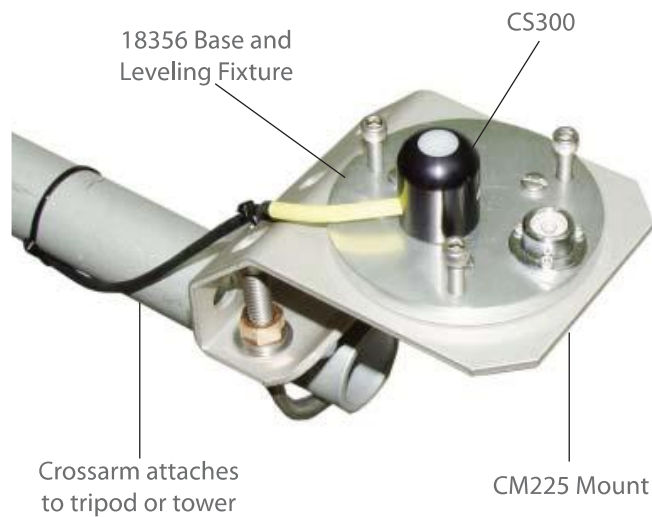


Figure 3.11 The associated leveling and holding fixtures of the CS3 pyranometer

Special leveling fixtures with a bubble level were supplied with the sensor to assure proper leveling and hence accurate measurements. Figure 3.11 shows the typical arrangement and fixing of CS3 and associated fixture to a holding arm.

3.4.5 Data Acquisition System

Products from Campbell Scientific were used in this study to compose the data acquisition system. The CR1000 data logger is the core of this system. Three AM16/32 multiplexers were used to increase the measuring capacity of the system to more than 100 differential channels. NL115 Ethernet and compact flash module was used to store the collected data and to directly download these data to PC.

These three products compose the main parts of the system and are discussed in details in the following sections. The data recording, timing, downloading and presentation were controlled by the LoggerNet 4.1 software. To assure continues power supply and to prevent power failure a dual power supply system was used. This system composed of a rechargeable battery, which can provide power continuously for about three days. This battery is directly connected to a regulator, which receives power from a 220V AC source from the construction laboratory.

Figure 3.12 shows the CR1000 data logger, which was used as the core of the data acquisition system. The CR1000 has eight differential (16 single-ended) channels. Several AM16/32 multiplexers can be connected to the CR1000 to increase the number of measurement sensors. CR1000 can operate in a temperature range of -55° to +85°C. The data logger has a built in temperature sensor to measure the temperature of the panel. The used data logger has a built in 6 MB flash memory for the operating system and data storage. The storage capacity of the CR1000 was increased using a 2 GB compact flash card. The data logger can be directly connected to a computer or a laptop using a built in serial RS-232. The CR1000 data logger is housed in a weather-resistant enclosure, which enables it to work under harsh conditions.

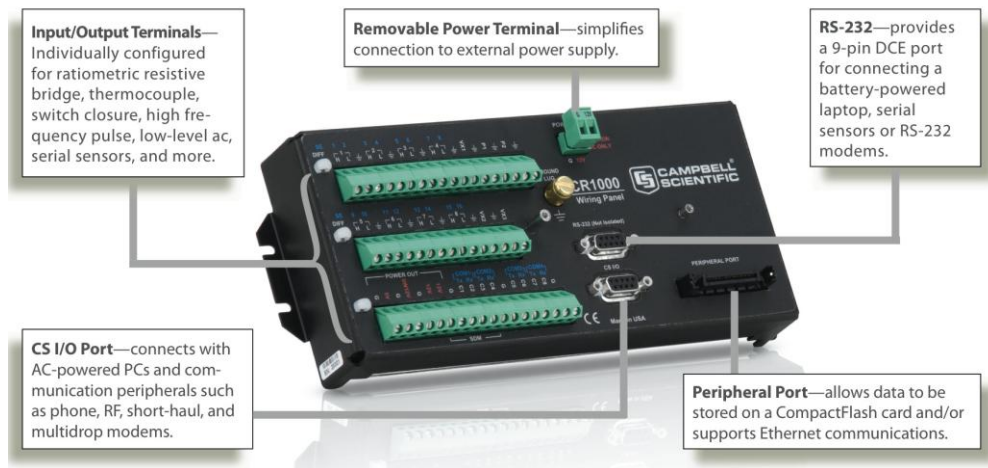


Figure 3.12 The CR1000 data logger

Three AM16/32 multiplexers from Campbell Scientific were used with the CR1000 data logger to provide an additional 96 differential channels for thermocouples. Figure 3.13 shows the AM16/32 multiplexer. This multiplexer can be used to measure different types of sensors like thermistors, moisture sensors, strain gages, vibrating wires and others.



Figure 3.13 The AM16/32 channel multiplexer

Campbell Scientific's NL115 Ethernet/compact flash module provides two independent capabilities: (1) enables an Ethernet communications and (2) stores data on a removable compact flash card, which allows the CR1000 to communicate over a local network or even a dedicated internet connection via TCP/IP. NL115 connects directly to the 40-pin peripheral port on the CR1000 data logger. Figure 3.14 shows

the NL115 Ethernet/compact flash module.



Figure 3.14 The NL115 Ethernet/compact flash module

3.5 Instrumentation

To study the temperature distribution in the concrete of the different parts of the box-girder, many thermocouples were installed in different positions. The distance between the thermocouples was not fixed. It differs from one position to another depending on the expected temperature gradients along or across these parts and temperature fluctuation at these positions. The center-to-center spacing between thermocouples ranges from only 40 *mm* up to 750 *mm*. In the following section, the preparing and installing of thermocouples and the other environmental sensors is explained in details.

3.5.1 Thermocouples Distribution

Sixty-two thermocouples were installed in the concrete of the box-girder in addition to two thermocouples were installed inside the box to measure the air temperature inside the box-girder. The sixty-two thermocouples were divided into four groups. The first is the South-Web (SW) thermocouples, which consists of 18 thermocouples. Similarly, the North-Web (NW) consists of 18 thermocouples. On

the other hand, the third and fourth are the Top-Slab (TS) and Bottom-Slab (BS) groups, which consist of 17 and 9 thermocouples, respectively.

The thermocouples of the top and bottom slabs (flanges) distributed along the centerline of the slabs spacing at a distance of 750 *mm* except along the cantilever portion of the top slab where thermocouples spaced at 500 *mm*. In addition to these thermocouples, the top slab has three sections, while the bottom slab has one section where three thermocouples were distributed vertically across the 200 *mm* thickness of the slab. Two of these sections were located at 500 *mm* from the free ends of the cantilever portions of the top slab, while the other two sections were located at the centers of the top and the bottom slabs.

The southern and the northern webs have the same thermocouple distribution. The distances between thermocouples in the webs differ from those along slabs and differ within the depth of the web itself. The spacing between thermocouples starts at 40 *mm* for the highest 6 thermocouples, passing through spacings of 200 *mm* and 400 *mm*, and ending at spacing of 50 *mm* between the lowest five thermocouples. The label of the south web thermocouples starts with SW1 and ends with SW18. Similarly, the north web thermocouples have labels of NW1 to NW18. The thermocouples of the top and bottom slabs have the labels of TS1 to TS17 and BS1 to BS9 respectively. Table 3.3 lists the coordinates of all of the 62 thermocouples.

Table 3.3 Coordinates of the 62 thermocouples considering the 0,0 point at the center of the lower Face of the bottom slab.

TC No.	X (m)	Y (m)	TC No.	X (m)	Y (m)
SW1	-2.25	2.4	NW14	2.25	0.2
SW2	-2.25	2.36	NW15	2.25	0.15
SW3	-2.25	2.32	NW16	2.25	0.1
SW4	-2.25	2.28	NW17	2.25	0.05
SW5	-2.25	2.24	NW18	2.25	0
SW6	-2.25	2.2	TS1	-3.625	2.3
SW7	-2.25	2.0	TS2	-3.125	2.4
SW8	-2.25	1.6	TS3	-3.125	2.3
SW9	-2.375	1.2	TS4	-3.125	2.2
SW10	-2.25	1.2	TS5	-2.625	2.3
SW11	-2.125	1.2	TS6	-1.5	2.3
SW12	-2.25	0.8	TS7	-0.75	2.3
SW13	-2.25	0.4	TS8	0	2.4
SW14	-2.25	0.2	TS9	0	2.3
SW15	-2.25	0.15	TS10	0	2.2
SW16	-2.25	0.1	TS11	0.75	2.3
SW17	-2.25	0.05	TS12	1.5	2.3
SW18	-2.25	0	TS13	2.625	2.3
NW1	2.25	2.4	TS14	3.125	2.4
NW2	2.25	2.36	TS15	3.125	2.3
NW3	2.25	2.32	TS16	3.125	2.2
NW4	2.25	2.28	TS17	3.625	2.3
NW5	2.25	2.24	BS1	-2.375	0.1
NW6	2.25	2.2	BS2	-1.5	0.1
NW7	2.25	2.0	BS3	-0.75	0.1
NW8	2.25	1.6	BS4	0	0.2
NW9	2.375	1.2	BS5	0	0.1
NW10	2.25	1.2	BS6	0	0
NW11	2.125	1.2	BS7	0.75	0.1
NW12	2.25	0.8	BS8	1.5	0.1
NW13	2.25	0.4	BS9	2.375	0.1

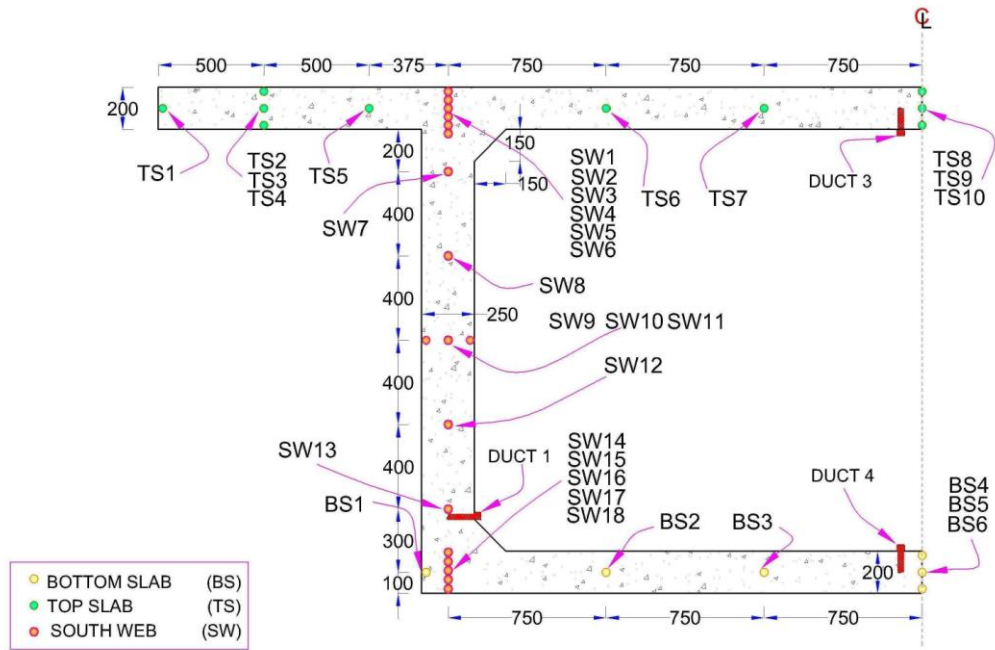


Figure 3.15 Thermocouples distribution of the southern half of the box-girder (all dimensions are in *mm*)

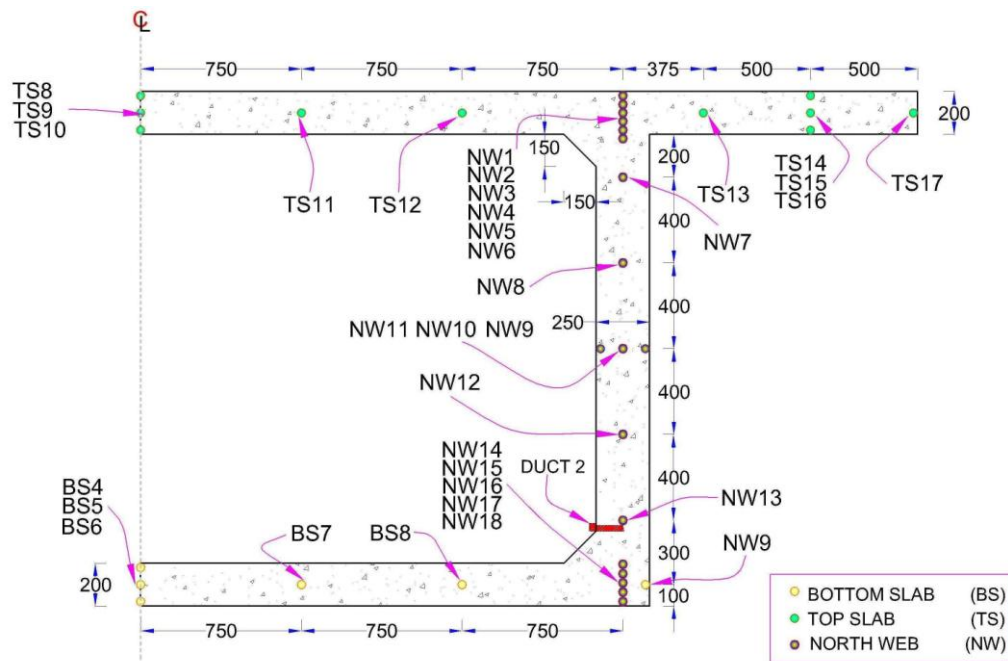


Figure 3.16 Thermocouples distribution of the northern half of the box-girder (all dimensions are in *mm*)

The distribution of the 62 thermocouples is clearly illustrated in Figures 3.15 and 3.16 for the southern half and the northern half of the box-girder, respectively. In Figures 3.15 and 3.16, both the location of thermocouple wires and the location of the wire exit duct for each group of wires are well illustrated.

3.5.2 Thermocouples Preparations and Instrumentation

Steel bars with nominal diameter of 16 *mm* were used to fix thermocouples in their proposed positions that are shown in Figures 3.15 and 3.16 and listed in Table 3.3. The lengths of the transverse bars in the top and bottom slabs were 7.25 *m* and 4.75 *m*, respectively, while the length of the vertical bars in the top and the bottom slabs was 200 *mm* only, which is the thickness of the slabs. On the other hand, the length of the vertical bars in the webs was equal to the height of webs, which is 2.4 *m*, while the length of the central perpendicular bars was 250 *mm*, which equals the thickness of the webs.

Figure 3.17 shows the tools used to prepare the thermocouple bars. The main parts of these tools were; flexible rubber tubes, plastic adhesive tapes, labels and labeling accessories, and a temperature measurement unit, in addition to the steel bars and the thermocouples.

Before the fixing of the thermocouples on the steel bars, the steel bars were covered by the flexible rubber tube. The rubber tube was then exposed to heat so that it fits the bars. The material of the rubber tube is designed for this function. The aim of this process is to assure the isolation of the steel bars from the surrounding concrete and to isolate thermocouples from the steel bars. This isolation technique is enough to assure that thermocouples read concrete temperature only, and prevent any possible electrical problems that may occur if the isolation layers of the thermocouples are corrupted by any means. Figure 3.18 shows the rubber tube and the steel bars after covering with and treatment of the rubber tubes.



Figure 3.17 Tools used to prepare the thermocouple bars



Figure 3.18 Covering the steel bars with the rubber tubes

The thermocouples were then fixed in positions one by one and their wires taped together using an adhesive tape. Before fixing the next thermocouple, each thermocouple was labeled according to its proposed location. Labels were printed on plastic sheets. After the fixing of all thermocouples of each bar, the wires were then covered by the second isolation layer, which composed of two layers of a 50 mm width adhesive tape as shown in Figure 3.19. This isolation layer used to prevent

any possible damage of thermocouple wires during the pouring of concrete and protect them from chemical attacks during their design life.



Figure 3.19 Covering of thermocouple wires with the second isolation layer

The extensions of the thermocouple wires of each bar were then taped together and covered with the second isolation layer. The end 0.5 *m* of each wire was left free to simplify the connection with the data logging system. Figure 3.20 shows the main four bars of the top slab (7.25 *m*), the bottom slab (4.75 *m*), and the south and north webs (2.4 *m* each) after the completion of their preparations.

The thermocouples were checked and calibrated before fixing on bars. After fixing all thermocouples of each bar, these thermocouples were checked again once using an electrical thermostat as shown in Figure 3.21. This is to assure that there is no any problem in any of the used thermocouples before fixing in place and concrete pouring.

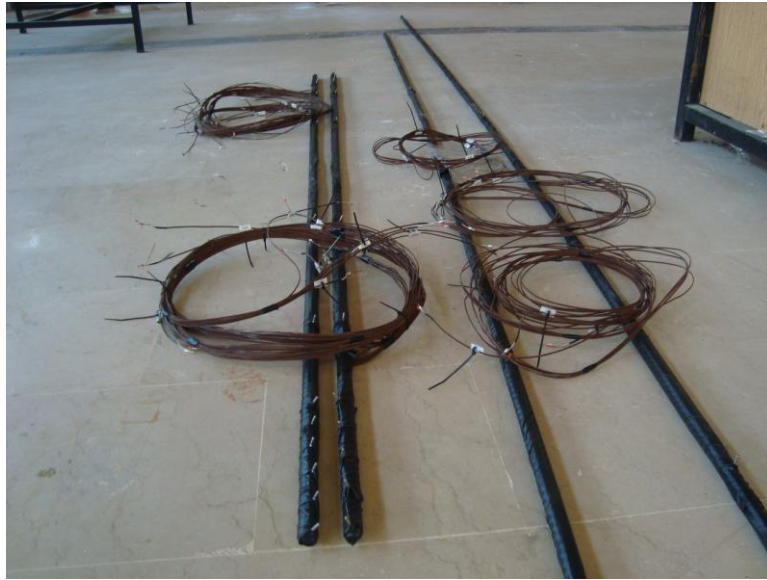


Figure 3.20 The four main thermocouple bars after thermocouples fixing

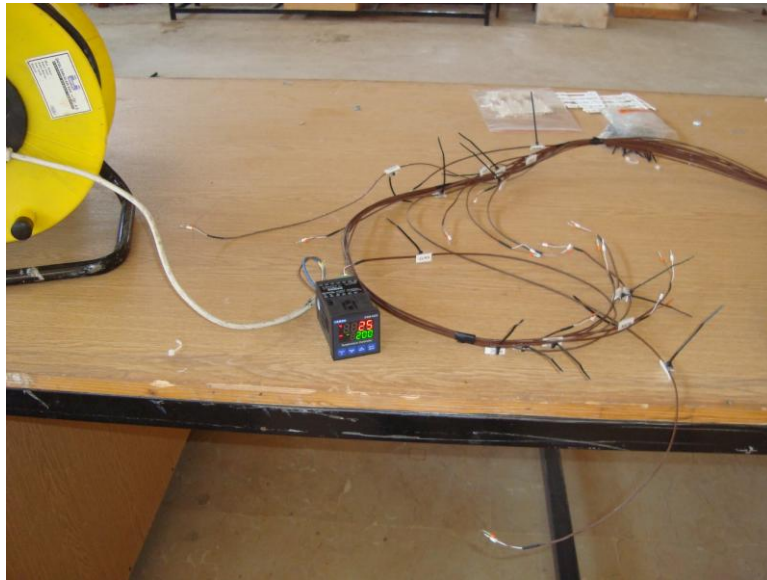


Figure 3.21 Checking of all thermocouples using an electrical thermostat

Figure 3.22 shows the final stage of thermocouples instrumentation. This stage is the fixing of these thermocouples in their places in the formwork. The vertical thermocouple bars were fixed in places using perpendicular steel bars that fit the thickness of the webs as shown in Figure 3.22. Similar procedure was used for the thermocouple wires in the top and bottom flanges. However, plastic and steel chairs were used to assure the setting of these bars at the required positions.

Pipe fittings with 50 *mm* diameters were used as exit ducts for the thermocouple wires from the concrete cores as shown in Figure 3.22. These exit ducts were used to assure safe exit for the thermocouple wires out of the reinforced concrete webs and slabs.



Figure 3.22 Fixing of thermocouple wires in their positions

3.5.3 Data Acquisition System and Connecting of Thermocouples

The data acquisition system, which is composed mainly of the CR1000 data logger and the AM16/32 multiplexers in addition to the other components, was contained in two environmental enclosures as shown in Figures 3.23 and 3.24. The first enclosure contains the CR1000 data logger, the NL115 Ethernet module, the power supply, and the backup rechargeable battery as shown in Figure 3.23. The second enclosure on the other hand, contains the AM16/32 multiplexers as shown in Figure 3.24.

All thermocouples were connected to their designed pins in the data acquisition system before concrete pouring as shown in Figure 3.24. The thermocouple labels were used as an index to locate the correct multiplexer pin for each thermocouple.



Figure 3.23 The CR1000 Data logger, the NL115 Ethernet module, the power supply, and the backup rechargeable battery that contained in the first enclosure

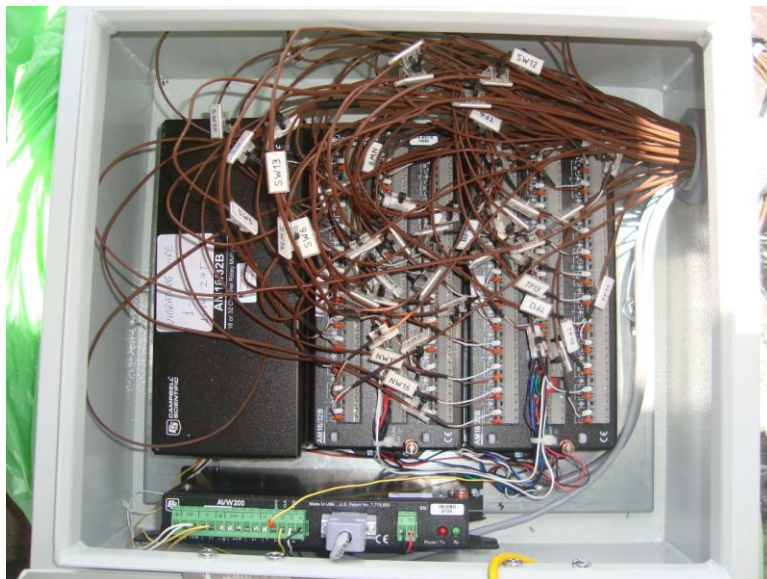


Figure 3.24 The second enclosure that contains the AM16/32 multiplexers and the thermocouples connected to the AM16/32 multiplexers



Figure 3.25 Installation of the environmental sensors in their permanent location

3.5.4 Instrumentation of Environmental Sensors

The three environmental sensors, namely, the solar radiation sensor, the ambient air temperature sensor, and the wind speed sensor were connected to the CR1000 data logger directly. The Readings from these sensors were started before the pouring of the concrete of the box-girder. The three sensors were fixed temporarily to a steel bar and a wood plank during the concrete pouring and the curing period. After the removal of all formworks and during the installation of the exterior isolation boards, the sensors were fixed on their permanent location to the concrete of the top slab as shown in Figure 3.25.

3.6 Control Specimens

During the pouring process of the box-girder and from the same concrete of box-girder, cube and cylinder control specimens were cast to measure some physical properties of concrete. Nine cylinders were prepared in addition to four cubes. The cylinders were $150 \times 300 \text{ mm}$, while the cubes were 150 mm . The concrete cubes and the cylinders were used to measure the compressive strength of concrete at age 28 days. The average compressive strength of the cubes was 35 MPa , while the average compressive strength of the cylinders was 28.9 MPa .

CHAPTER FOUR

THE EXPERIMENTAL RESULTS

4.1 General

The construction process and the instrumentation of the experimental box-girder were explained in details in chapter three. The measurements of the environmental sensors and the concrete thermocouples started at the date of concrete casting of the box-girder in 25-May-2013 and continued for more than one year up to 3-July-2014. The results of the experimental box-girder segment are discussed in details in this chapter.

The chapter focuses on the environmental recorded data of the whole period extended from the casting of concrete in 25-May-2013 to 3-July-2014, which include the air temperature records, the wind speed records, and the solar radiation records. Moreover, the temperature distributions in different thermocouples distributed in the different parts of the box-girder are studied and discussed for the early age period that extended for few days from concrete casting. For this period, the effects of cement hydration on the thermal behavior of the box-girder are studied. Finally, this chapter presents and discusses the temperature distributions and the vertical and lateral temperature gradients along and across the different parts of the box-girder for selected days from the four seasons of the year.

4.2 Air Temperature, Wind Speed, and Solar Radiation Records

The environmental records from the air temperature probe, the three-cup anemometer, and the global solar radiation pyranometer are presented in this section. The boundary thermal loads that control the heat transfer in the box-girder segment are controlled by these measurements, which reveals the importance of the presentation of the environmental records.

4.2.1 Air Temperature Records

For the whole period extended from 25-May-2013 to 3-July-2014, Figures 4.1 through 4.3 show the daily maximum and the daily minimum air temperatures in addition to the difference between the daily maximum and minimum temperatures. The maximum air temperature along this period was 38.4°C , which was recorded in 3-July-2014, while the minimum air temperature was recorded in 12-December-2013 and was -8.7°C . On the other hand, the maximum daily temperature difference between the daily maximum and minimum air temperatures was recorded in 11-October-2013 and was 23.6°C .

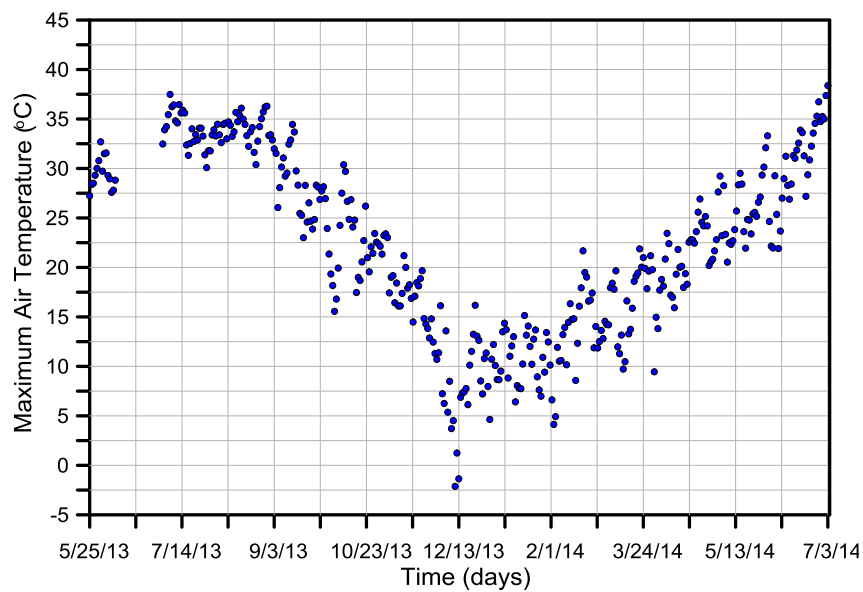


Figure 4.1 Daily maximum air temperatures for the period from 25-May-2013 to 3-July-2014

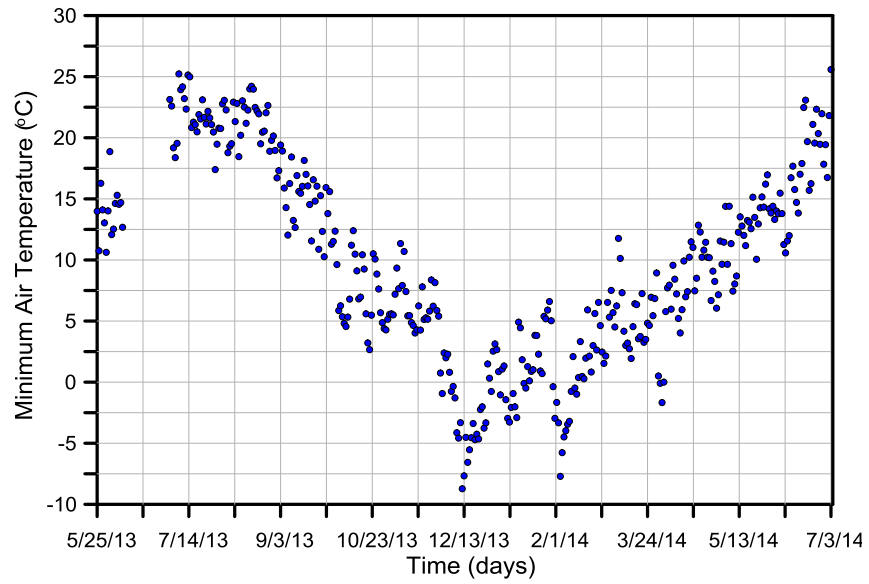


Figure 4.2 Daily minimum air temperatures for the period from 25-May-2013 to 3-July-2014

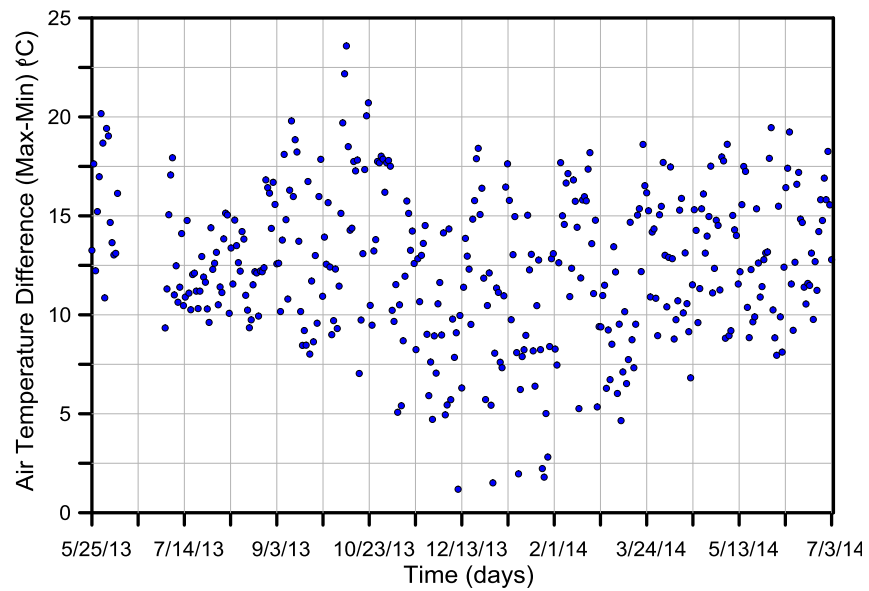


Figure 4.3 Difference between daily maximum and minimum air temperatures for the period from 25-May-2013 to 3-July-2014

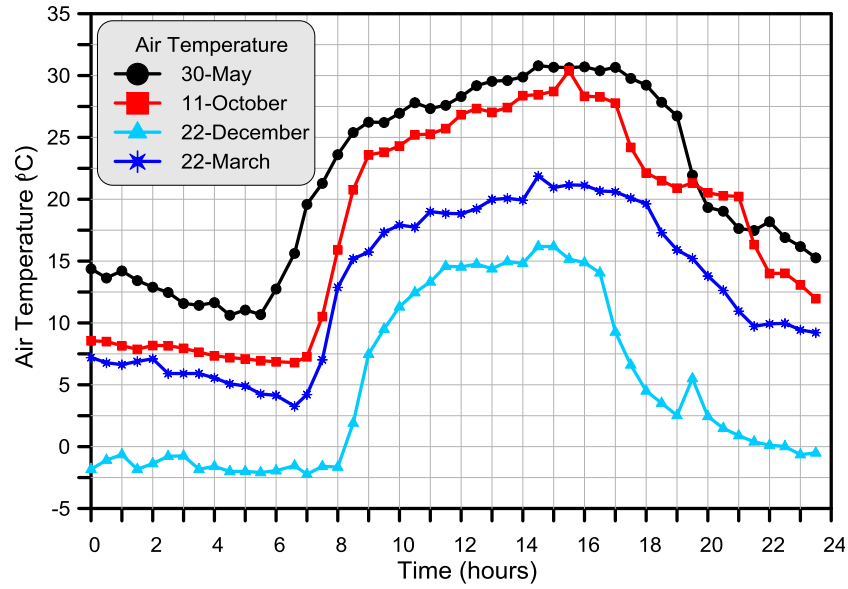


Figure 4.4 Hourly air temperatures for days with maximum air temperature differences from the four seasons

Figure 4.4 shows the daily air temperature distributions for four selected days from the four seasons. The selected days represent the days at which the maximum daily temperature difference between the daily maximum and minimum air temperatures occurred. These days were 30-May-2013, 11-October-2013, 22-December-2013, and 22-March-2014. The corresponding daily air temperature differences of these days were 20.2°C, 23.6°C, 18.4°C, and 18.6°C, respectively.

4.2.2 Wind Speed Records

The convection cooling of the surfaces of the box-girder depends mainly on the temperature of the surrounding air in addition to its speed. Thus, the measurement of wind speed for each time step is important to understand the heat transfer process in the concrete box-girder. Figure 4.5 shows the daily maximum wind speed for the complete record period, while Figure 4.6 shows the minimum daily wind speed for the same period. The recorded maximum wind speed along this period was 7.1 *m/s*, while the minimum was 0 *m/s*. The daily average wind speed was in the range of 0 to 4.1 *m/s* as shown in Figure 4.7.

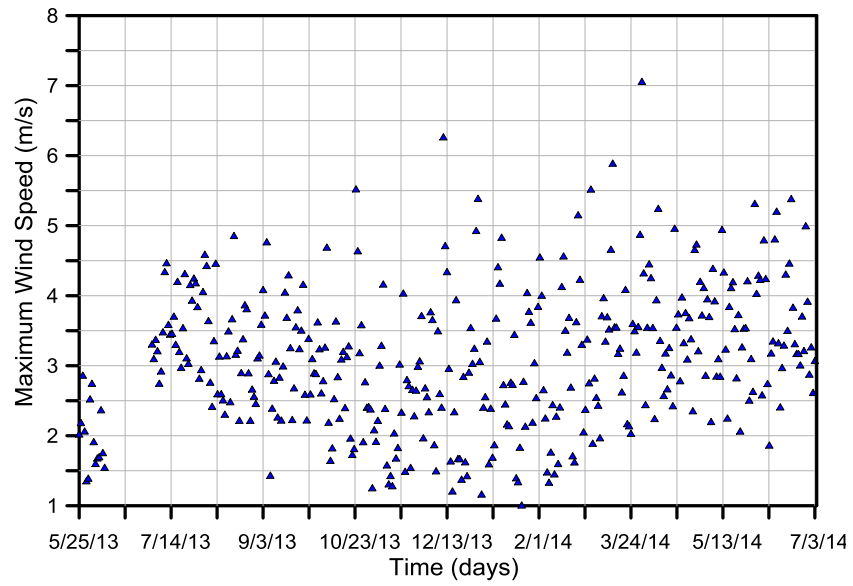


Figure 4.5 Daily maximum wind speeds for the period from 25-May-2013 to 3-July-2014

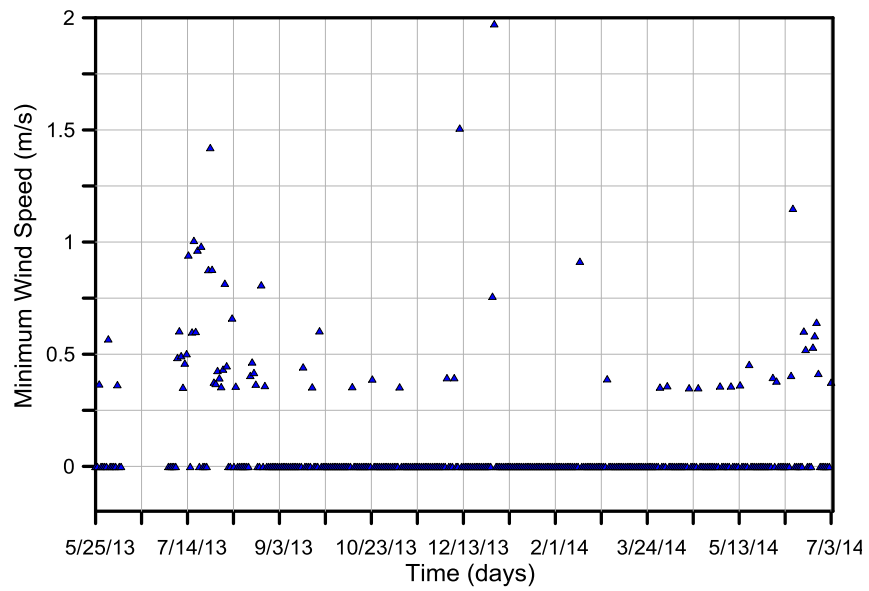


Figure 4.6 Daily minimum wind speeds for the period from 25-May-2013 to 3-July-2014

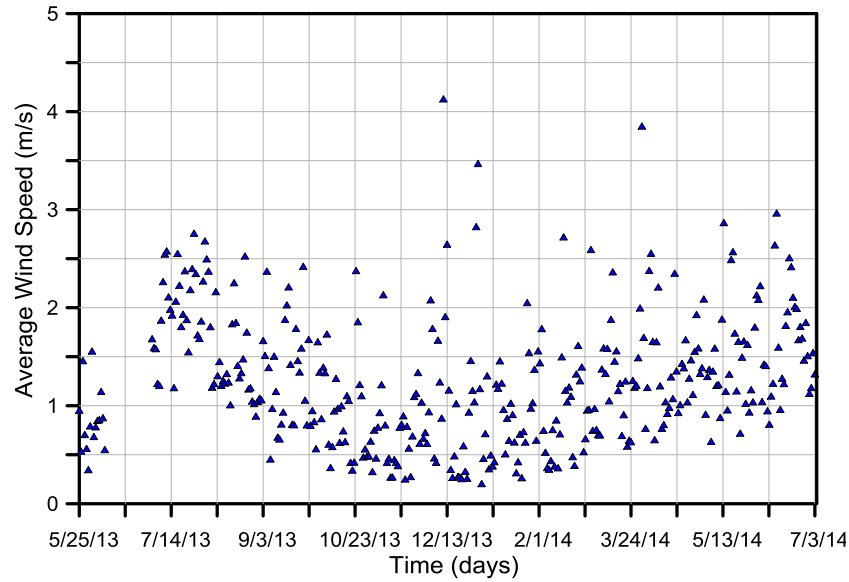


Figure 4.7 Daily average wind speeds for the period from 25-May-2013 to 3-July-2014

4.2.3 Solar Radiation Records

Global hourly solar radiation records were measured by the installed pyranometer for the period extended from 25-May-2013 to 3-July-2014. The daily maximum hourly solar radiation for this period is plotted in Figure 4.8. The daily maximum hourly global solar radiation in this period was recorded in 2-June-2013, which was 1200 W/m^2 . On the other hand, in some winter heavy cloudy days, very low solar radiation intensities were recorded so that its maximum was less than 50 W/m^2 in some days as shown in Figure 4.8.

Figure 4.9 shows the hourly solar radiation distribution for selected days that represents the days of maximum solar radiation during the four seasons. These days were 2-June-2013, 6-October-2013, 3-December-2013, and 16-April-2014 as shown in the figure. The corresponding daily maximum solar radiation records for these days were 1200, 1038, 796, and 1129 W/m^2 , respectively.

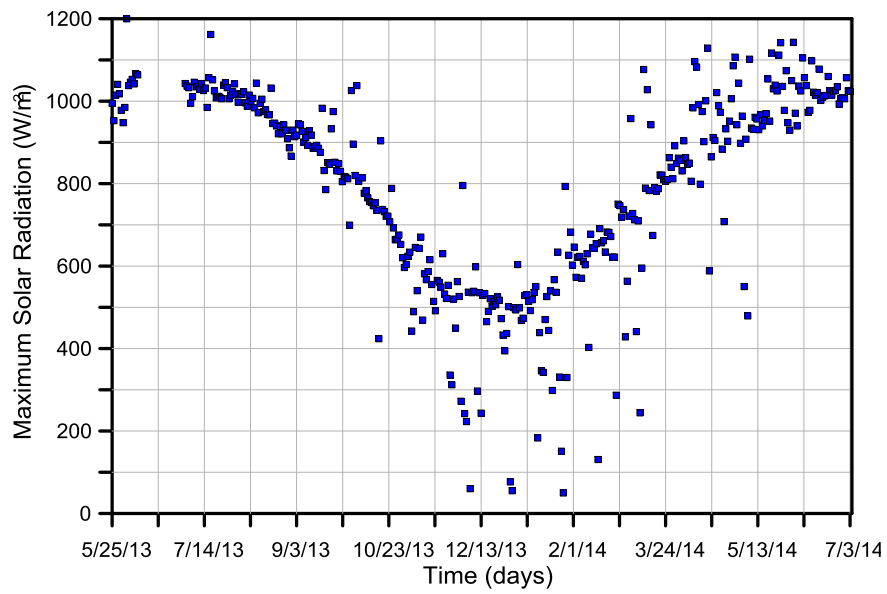


Figure 4.8 Daily maximum hourly solar radiations for the period from 25-May-2013 to 3-July-2014

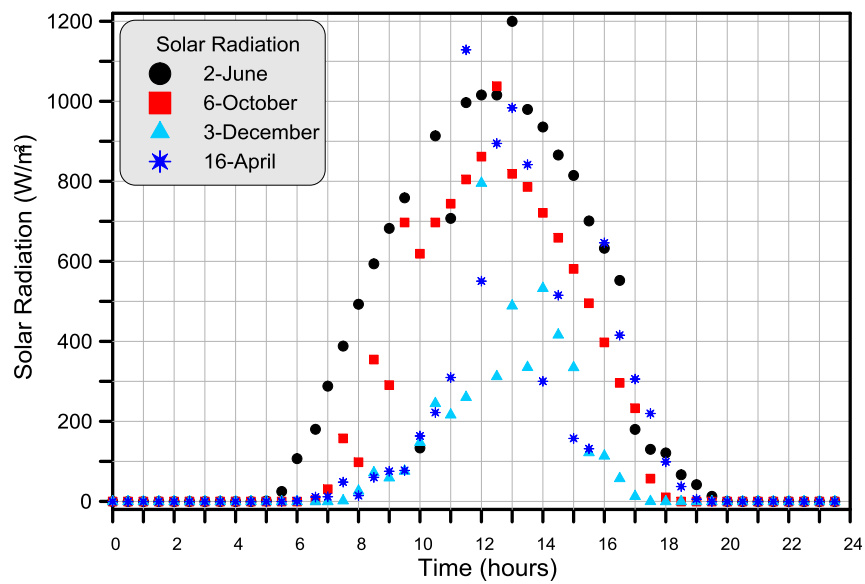


Figure 4.9 Hourly global solar radiations for days with maximum solar radiation from the four seasons

4.3 Temperature Distributions during the Early Age of the Box-Girder

During the fresh state of the concrete (within the first few days after casting), the thermal loads affecting the heat transfer in the box-girder segments differs from those along the rest of the box-girder life. Two main differences exist. The first is the heat produced from the hydration of cement, while the second is the different boundary conditions where formworks encasing many surfaces of the box-girder segment. The temperature distributions under the effect of both the cement hydration heat and the temporary surface formworks are discussed in this section.

4.3.1 Air Temperature and Solar Radiation

The sky during the first few days after concrete casting was partially cloudy to sunny. Figure 4.10 shows the solar radiation and air temperature during the first week after concrete casting. As shown in Figure 4.10, solar radiation was noticeably fluctuated during the day hours of the casting day (25-May). In the following day, solar radiation was also fluctuated, which reflects that the sky was cloudy during the first two days. The 27th of May (the third day) was a sunny day, which is clear from the continuous solar radiation distribution shown in Figure 4.10. It is clear from the figure that the subsequent three days were cloudy, while the last two days were sunny.

Figure 4.10 shows that the temperature of air during the first 180 hours ranged from 10.6 to 32.7°C, while the recorded maximum hourly global solar radiation was 1040 W/m^2 . The daily average wind speed for the same period was in the range of 0.5 to 1.5 m/s , while the recorded maximum wind speed was 2.9 m/s .

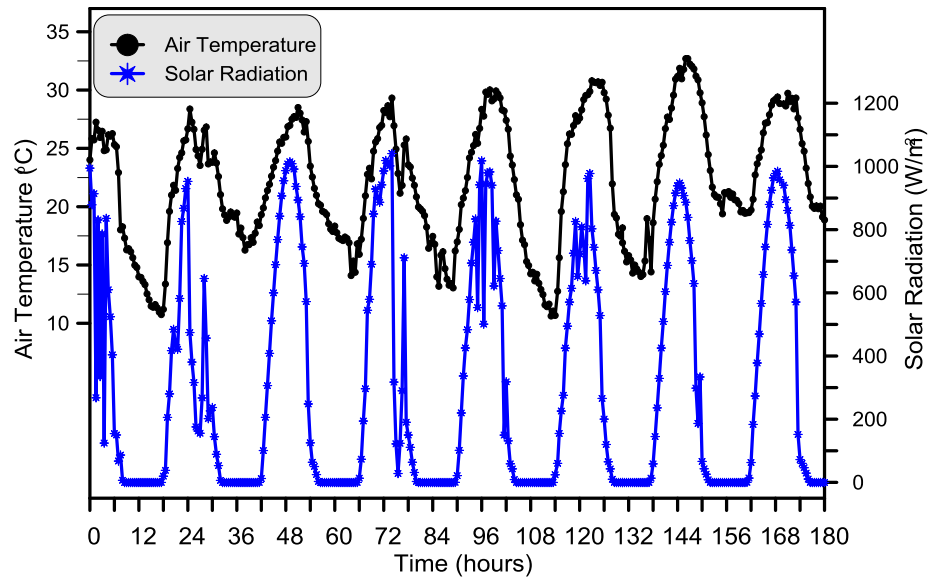


Figure 4.10 Air temperature and global solar radiation for the first 180 hours from concrete casting of the box-girder segment

4.3.2 Temperature Variation with Time for Specific Thermocouples

Figure 4.11 shows the temperature-time curves for the top 7 thermocouples along the centerline of the south web. SW1 is the thermocouple installed at the top surface of the box-girder, SW2 installed 40 *mm* below SW1, SW4 installed 120 *mm* below the top surface, while SW6 and SW7 are the thermocouples installed deeper at 200 *mm* and 400 *mm* below the top surface.

It should be noted that the interior and the exterior walls of the webs, in addition to the bottom surfaces of the top slab and the bottom slab were isolated from the surrounding environment by the formwork, while the top surfaces of the top and bottom slabs were exposed.

Figure 4.11 shows that the heat released from cement hydration affected the temperature of concrete during the early 48 hours noticeably. A significant temperature rise occurred after about 4 hours from the placing of concrete. The temperature then increased continuously to reach its peak after about 12 hours from concrete casting. The hydration heat was then decreased noticeably during the following 24 hours. Figure 4.11 shows that the effect of hydration heat on concrete temperatures almost diminished after four days, therefore and for better

visualization, the temperature-time curves are presented for only the early 96 hours in Figures 4.12 through 4.14.

It was recorded that the thermocouples along the NW followed the same behavior of the SW thermocouples but with slightly lower temperatures as shown in Figure 4.12. As shown in Figures 4.11 and 4.12, the effect of hydration heat on the temperature of concrete depends on the location of the thermocouple. Thermocouples on or close to the top surface followed the air temperature fluctuation showing lower dependency on the heat of hydration, while deeper thermocouples showed complete dependency on the hydration heat behavior. Thermocouples SW7 and NW7 are the thermocouples surrounded by the largest mass of concrete among other thermocouples, thus the heat released from the hydration of cement in the surrounding concrete has increased the temperature of these thermocouples during the first 12 hours from concrete casting in spite of the continuous decrease of air temperature during this period (night hours). The thermocouples SW7 and NW7 reached their maximum of about 52°C after about 30 minutes from the mid of the first night, thus after about 12 hours from the casting of the top slab. During the day hours of the next day, SW7 and NW7 showed continuous decrease with the decrease of the hydration heat of concrete regardless of the increase of air temperature as shown in Figures 4.11 and 4.12.

The surface thermocouples SW1 and NW1 on the other hand, followed the decrease of air temperature during the 12 hours after the concrete casting. Thus, effect of the heat of hydration on the surface thermocouples was very limited. Moreover, their temperatures increased during the next day following the increase of air temperature as shown in Figures 4.11 and 4.12. This is an expected result, since SW1 and NW1 are almost in direct contact with the ambient air temperature and are enclosed by the lowest amount of concrete.

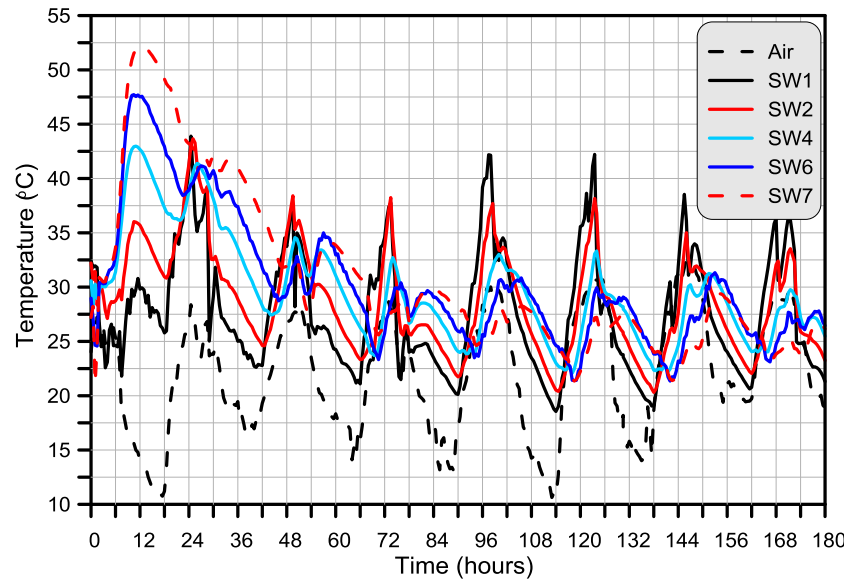


Figure 4.11 Temperature-time curves for selected thermocouples along SW during the first 180 hours

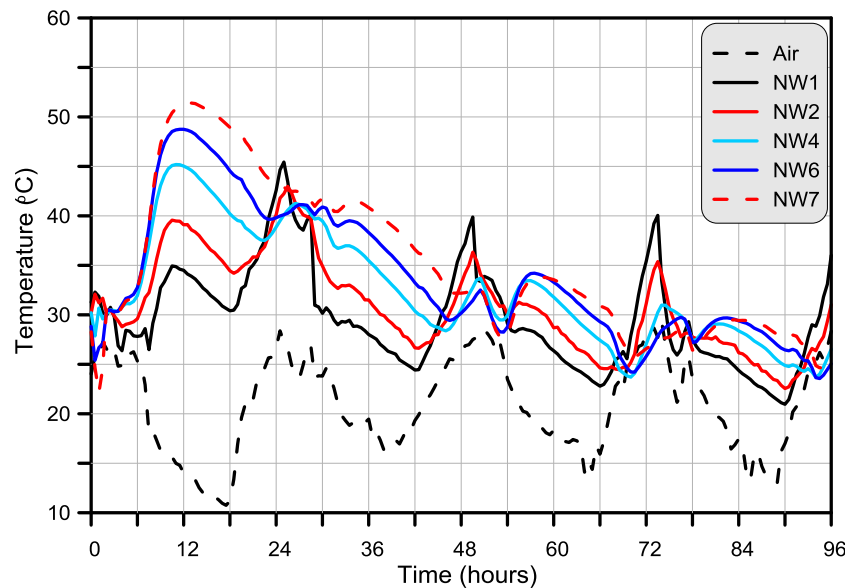


Figure 4.12 Temperature-time curves for selected thermocouples along NW during the first 96 hours

On the other hand, the thermocouples between SW1 and SW7 showed mixed behavior where they showed partial dependency on both the heat of hydration and the temperature of air. The degree of dependency relies on the location of thermocouples. As shown in Figure 4.11, SW6 seems to follow the same pattern of

SW7, but with lower temperatures. The recorded maximum temperatures of SW6 and NW6 were about 48°C, which occurred after about 10 hours from concrete casting. It is shown in the figures that the temperature of SW2 and NW2 has increased with the increase of hydration heat and then decreased with the decrease of air temperature, but with higher dependency on the fluctuation of air temperature. SW4 and NW4 on the other hand, showed similar behavior but were much affected by hydration heat behavior than by air temperature fluctuation.

Figure 4.13 shows the temperature-time curves of TS8, TS9, and TS10 across the thickness of the mid-width of the top slab. As shown in the figure, TS8, which is the top surface thermocouple, followed the same pattern of air temperature and showed minor dependency on hydration heat behavior during the first 12 hours. TS9 the mid-thickness thermocouple and TS10, which is installed at the lower surface where no direct contact with ambient air and with larger surrounding concrete volume showed stronger dependency on hydration heat than on air temperature during the early 24 hours. In the subsequent days and as the effect of hydration heat decreased, all thermocouples showed stronger dependency on air temperature fluctuation. Similar results were noticed for thermocouples BS4, BS5, and BS6 across the thickness of the bottom slab as shown in Figure 4.14.

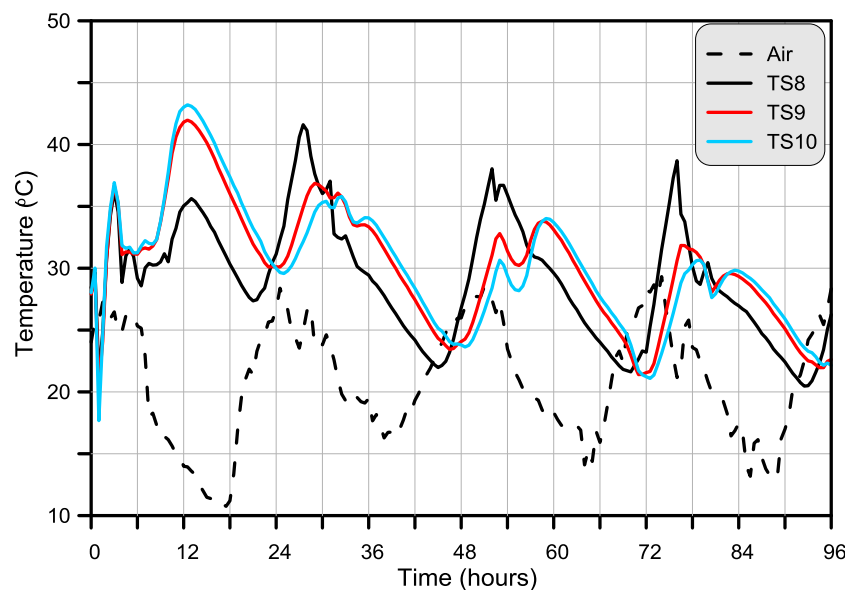


Figure 4.13 Temperature-time curves for selected thermocouples along TS during the first 96 hours

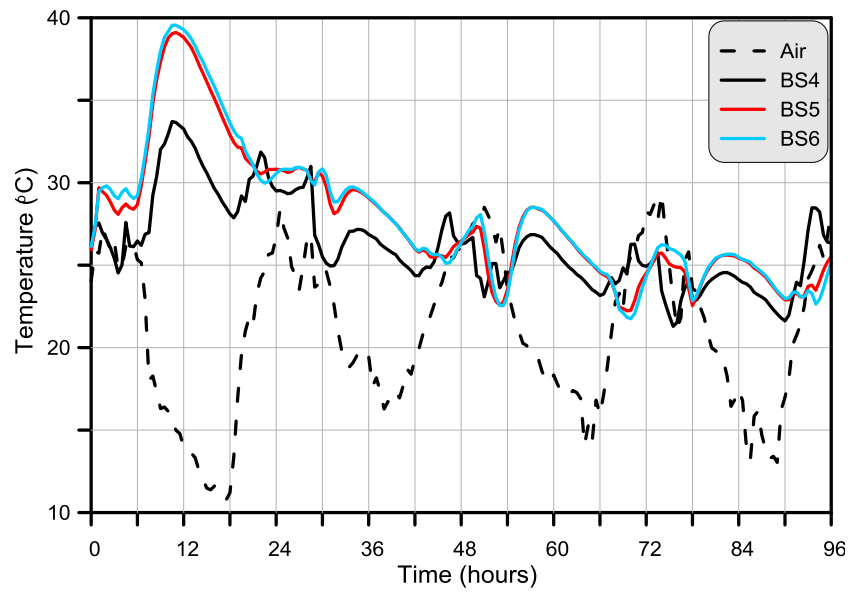


Figure 4.14 Temperature-time curves for selected thermocouples along BS during the first 96 hours

4.3.3 Vertical Temperature Distributions

During the day hours, the top surface of the girder receives higher solar radiation intensities and for longer periods than the other parts and surfaces. Due to the low concrete conductivity, the absorbed heat from the surfaces is conducted slowly to concrete interiors, and as a result, the temperature of the top surface during the hot midday hours (especially in summer) becomes much higher than concrete interiors. The temperature of the concrete layers that are closer to the top surface is higher than of layers deeper in the concrete, hence, a temperature distribution forms with a maximum temperature at the top surface and a minimum temperature at somewhere along the web. As sun sets, the solar radiation becomes zero, while the fluent of air on the exposed surfaces tends to cool the surface down via the heat convection. The convection continues cooling the top surface during the whole night hours, while the interiors of concrete still warm, which results in an inverse temperature distribution with a minimum temperature at the top surface and a maximum temperature at the interiors of the web. During the early age of concrete and because of the effect of the hydration heat, the normal expected vertical temperature distributions that explained above would no longer stand.

Figure 4.15 shows the vertical temperature distributions along the south web at 2:00 PM for the first six days. As shown in the figure, the temperature is nearly uniform along the depth of the box-girder in 25-May because only about one hour has passed after the concrete casting completion of the box-girder, hence, the initial temperature of concrete controls. The temperature of the top surface was lower than of the concrete interiors because of the lower temperature of air at that time. The temperature of concrete at 2:00 PM in 25-May was about 30°C, while air temperature at the same time was less than 19°C.

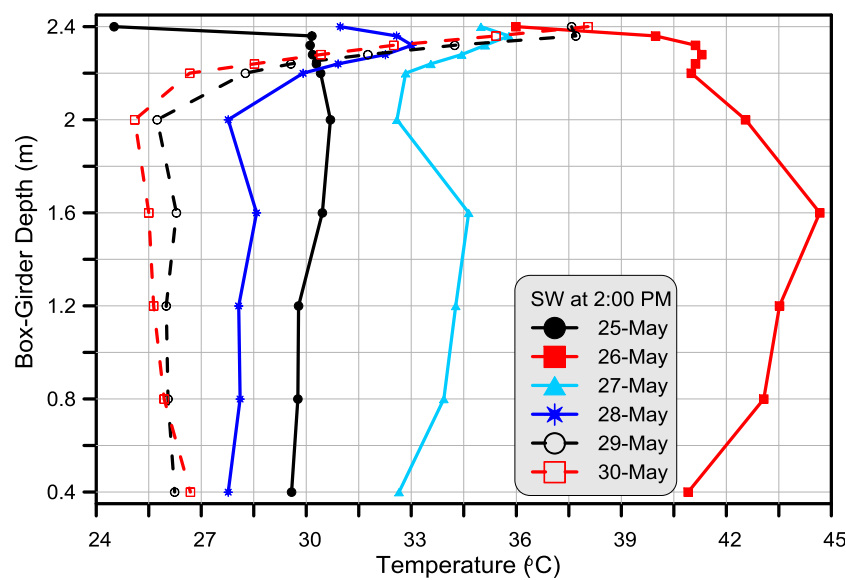


Figure 4.15 Vertical temperature distributions along the south web at 2:00 PM for the first 6 days

As shown in Figure 4.15, the temperature of concrete was high in the following day due to the effect of hydration heat, where the temperature increased as the distance from surfaces increased reaching a maximum of about 45°C at SW8 (0.8 m below the top surface). The temperature of the top surface and in spite of the direct exposure to solar radiation was lower than concrete interiors forming an inverse or a negative temperature distribution as shown in Figure 4.15. Thus, the heat released from cement hydration during the early age resulted in a negative temperature distribution at the hot day hours. As shown from the temperature distribution of the subsequent two days, this effect decreased gradually as the heat of cement hydration

set down within the next 48 hours. The vertical temperature distributions of 29 and 30-May show that the vertical temperature distribution became normal with a maximum temperature at the top surface and a minimum within the web after the diminishing of the effect of cement hydration.

Figure 4.16 shows that the heat of cement hydration increased the temperature of concrete interiors significantly in the first night (about 12 hours after concrete casting), while the top surface was cooled down due to air convection, resulting in higher negative temperature differences (gradients) at 2:00 AM of the first night. The temperature of the web increased up to about 52°C at SW7, while the temperature of SW1 on the top surface was about 27°C. Thus, a negative temperature gradient of about 25°C occurred at 2:00 AM of the first night because of the effect of hydration heat. This negative temperature gradient decreased gradually as shown in Figure 4.16 as time passed and as the concrete interiors cooled down with the decrease of the effect of hydration heat. The negative temperature gradients between the top surface and concrete interiors were about 17°C, 10°C, and 7°C at 2:00 AM in 27-May, 28-May, and 29 May, while it was about 6°C in 30-May and 31-May. Thus, the effect of the hydration heat on the vertical temperature distribution diminished after about three days.

Figures 4.17 and 4.18 show the vertical temperature distributions along the north web at 2:00 PM and 2:00 AM and for the same days compared in Figures 4.15 and 4.16. The figures confirm the results discussed for the vertical temperature distributions and show similar sequence of results as those discussed in Figures 4.15 and 4.16.

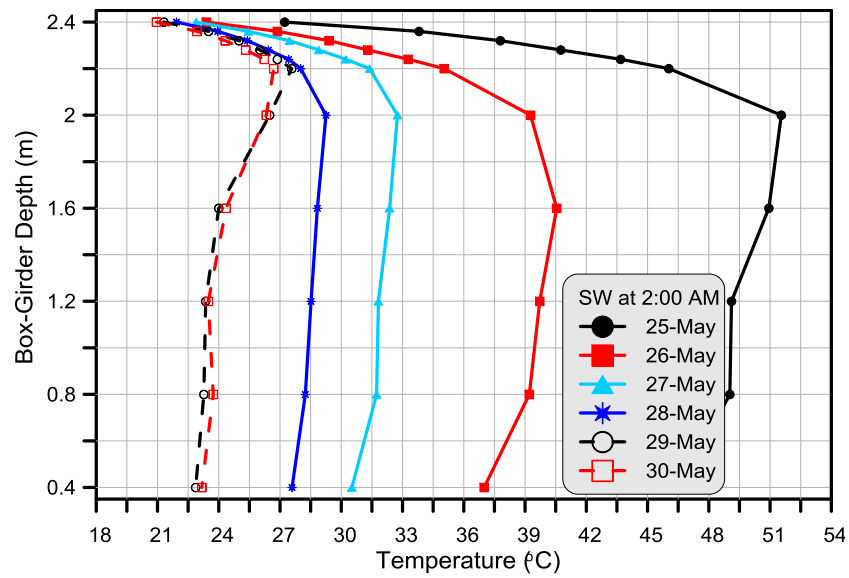


Figure 4.16 Vertical temperature distributions along the south web at 2:00 AM for the first 6 days

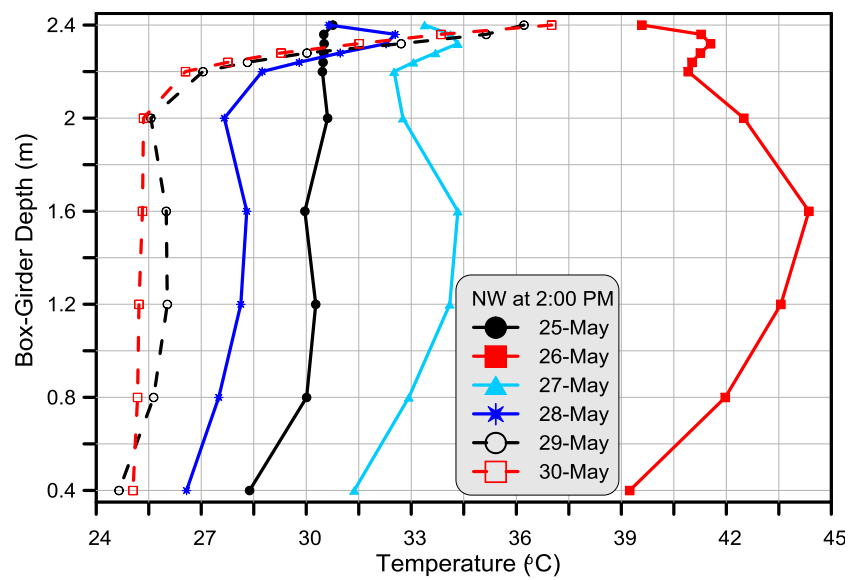


Figure 4.17 Vertical temperature distributions along the north web at 2:00 PM for the first 6 days

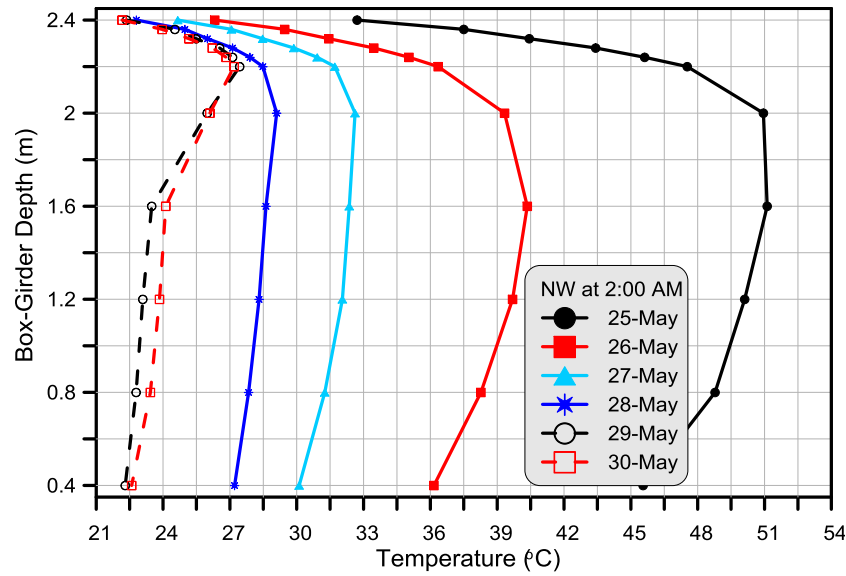


Figure 4.18 Vertical temperature distributions along the north web at 2:00 AM for the first 6 days

4.4 Temperature-Time Curves of Thermocouples

In this section, the variation of temperature with time along the complete studied period is presented for selected thermocouples from the four groups. Figures 4.19 to 4.28 show the daily maximum and minimum temperatures along thermocouples SW1, SW2, SW6, SW11, NW9, NW18, TS1, TS9, BS1, and BS5 for the period extended from July 2013 to July 2014.

The selected thermocouples, were chosen so that they can represent the temperature variation along the vertical and lateral members at different locations. SW1, SW2, and SW6 can show the effect of the thickness of concrete above the top thermocouples along the webs, while SW11 and NW9 can show the differences between the temperature variation of the exterior and the interior thermocouples across the central depth of webs. NW18 on the other hand, shows the variation at the bottom surface thermocouple along the webs. TS1 and TS9 are the edge and the central thermocouples of the top slab, while BS1 and BS5 are their corresponding thermocouples in the bottom slab.

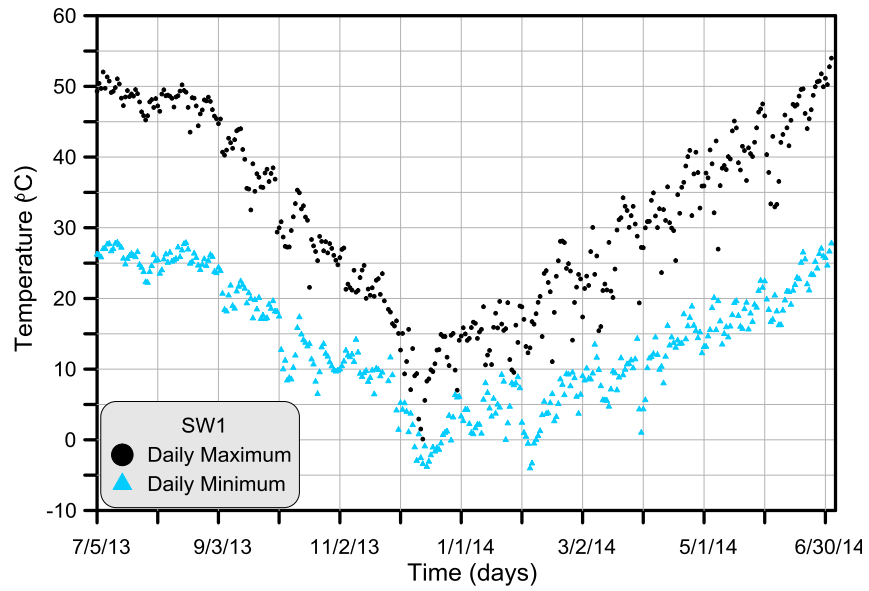


Figure 4.19 Daily maximum and daily minimum temperatures of thermocouple SW1 from July 2013 to July 2014

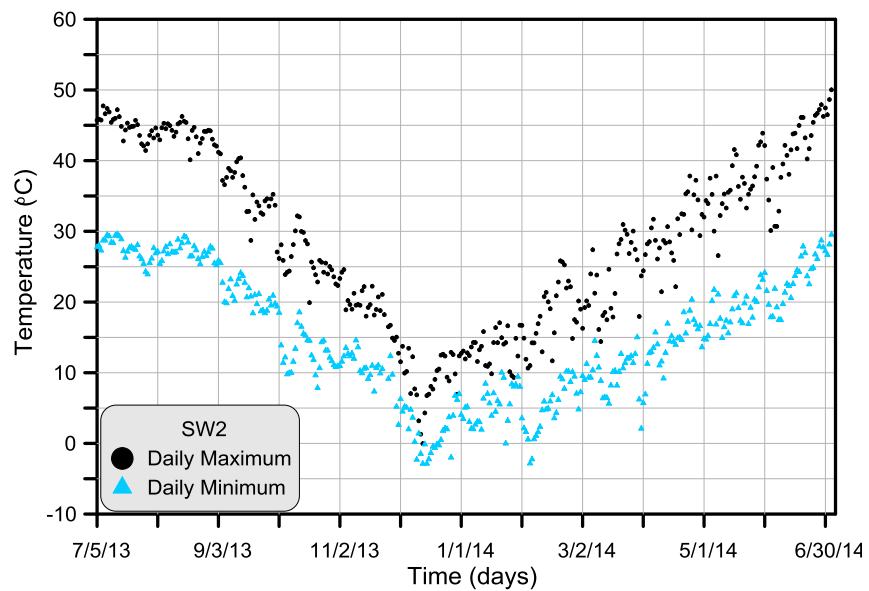


Figure 4.20 Daily maximum and daily minimum temperatures of thermocouple SW2 from July 2013 to July 2014

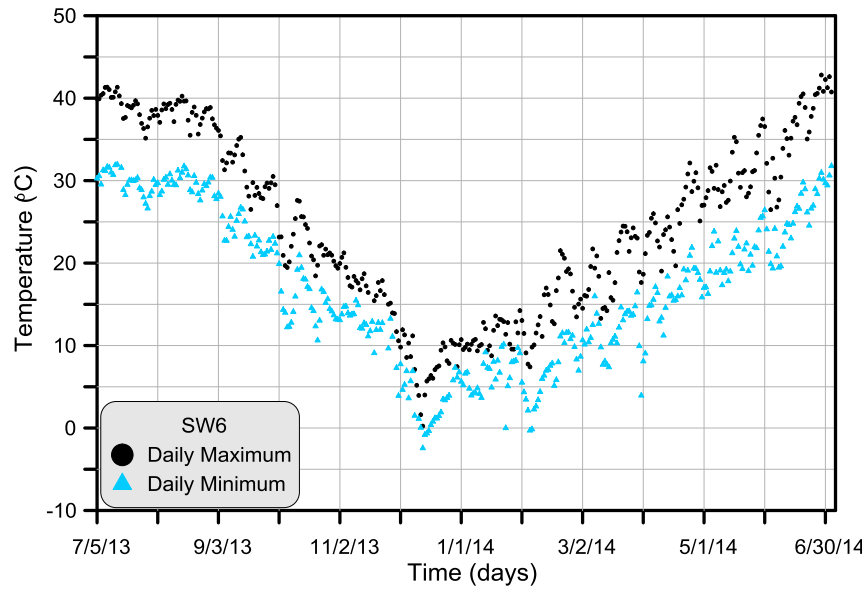


Figure 4.21 Daily maximum and daily minimum temperatures of thermocouple SW6 from July 2013 to July 2014

Comparison between Figures 4.19 to 4.21 shows that the variation in the daily maximum and daily minimum of the vertical webs' thermocouples is strongly affected by the location from the top surface, thus, from the direct exposure to the environmental thermal loads. SW1, the surface thermocouple showed higher variation between the daily maximum and the daily minimum than SW2, which in turn showed higher variation than SW6. Note that SW2 is 40 *mm* below the top surface, while SW6 is 200 *mm* below the top surface. The recorded maximum daily temperature differences (daily maximum - daily minimum) for SW1, SW2, and SW6 were 26.7°C, 21.6°C, and 18°C, respectively.

The comparison between NW9 (exterior surface) and SW11 (interior surface inside the cavity of the box-girder) clearly reveals that the temperature inside the box-girder exhibited much less fluctuation in the daily temperature than the opposite exterior thermocouples. As shown in Figures 4.22 and 4.23, the difference between the daily maximum and daily minimum temperatures was low in SW11, while it was higher in NW9. The recorded maximum daily temperature differences for SW9, SW11, NW9, and NW11 were 20.5°C, 10.4°C, 16.9°C, and 8.4°C, respectively. Since the solar radiation effect on the bottom surface is much lower than on the top surface, SW18 showed much lower daily variation than SW1 as shown in Figure 4.24.

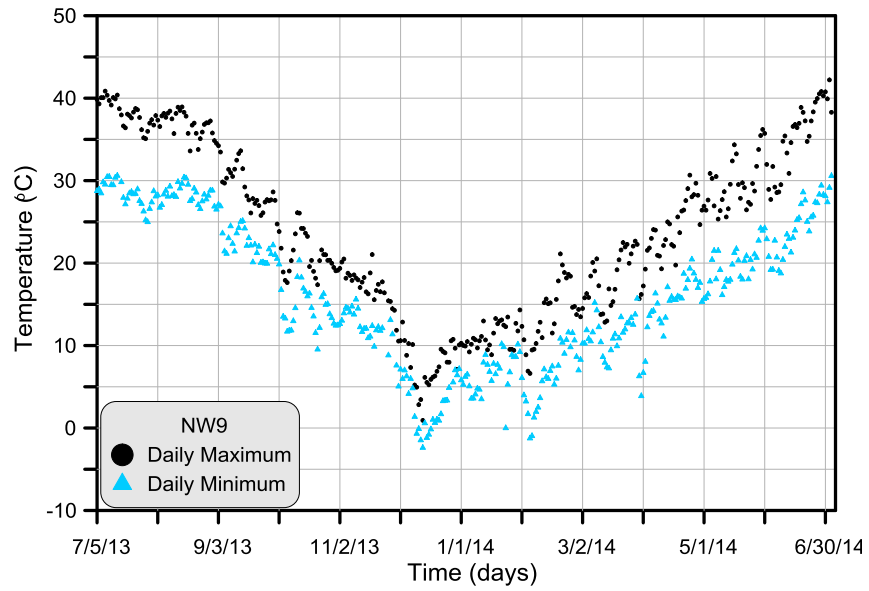


Figure 4.22 Daily maximum and daily minimum temperatures of thermocouple NW9 from July 2013 to July 2014

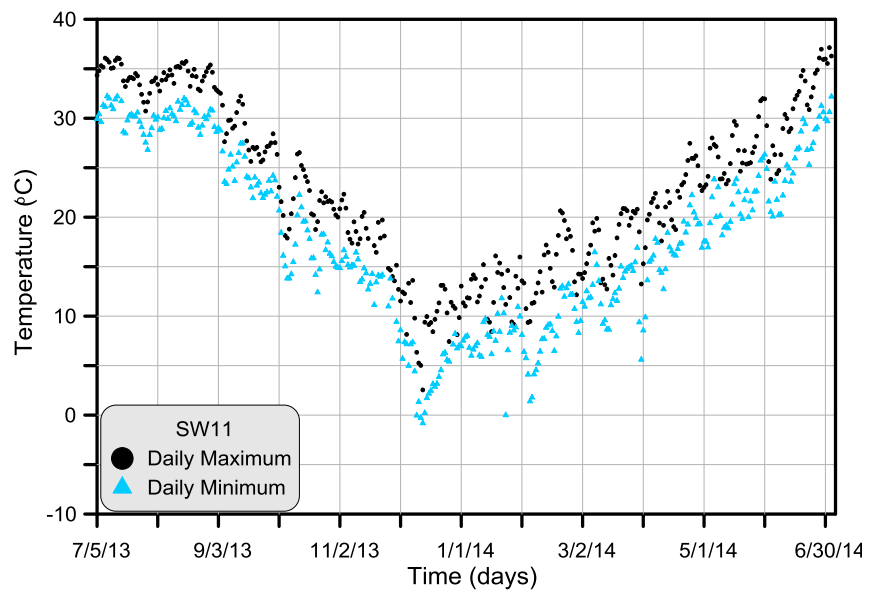


Figure 4.23 Daily maximum and daily minimum temperatures of thermocouple SW11 from July 2013 to July 2014

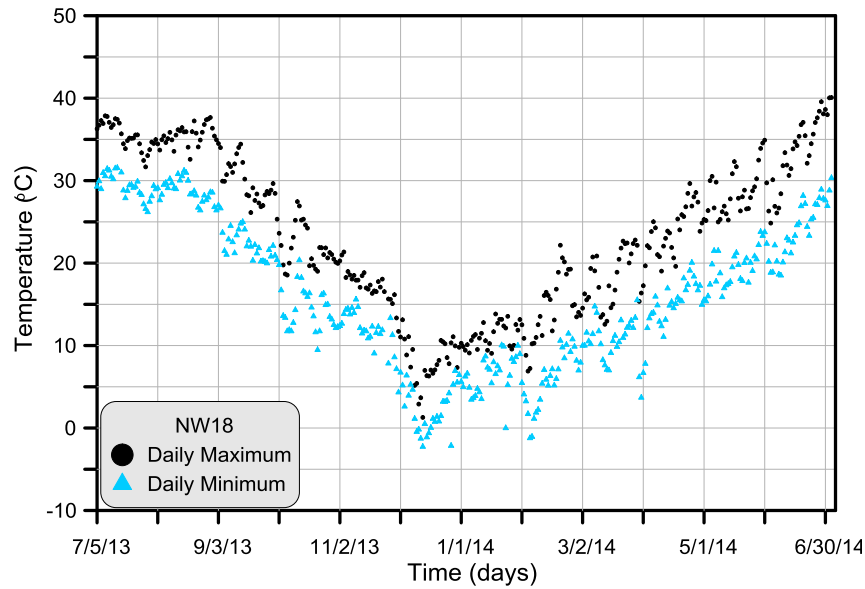


Figure 4.24 Daily maximum and daily minimum temperatures of thermocouple NW18 from July 2013 to July 2014

As shown in Figures 4.25 and 4.26, the exterior edge thermocouple TS1 showed higher daily temperature variation than the central thermocouple TS9. Due its direct exposure to air temperature, solar radiation, and wind cooling, TS1 showed much higher differences between the daily maximum and daily minimum temperatures than TS9. The recorded maximum daily temperature differences for TS1 and TS9 were 28.9°C and 15.9°C.

Figures 4.27 and 4.28 show that the bottom slab's exterior edge thermocouple BS1 and the bottom slab's central thermocouple BS5 showed lower degree differences compared to those between TS1 and TS9. This is an expected result because the effect of thermal loads, especially solar radiation, is much lower on the bottom slab than on the top slab due to the different locations and configurations. The recorded maximum daily temperature differences for BS1 and BS5 were 19.4°C and 9.2°C.

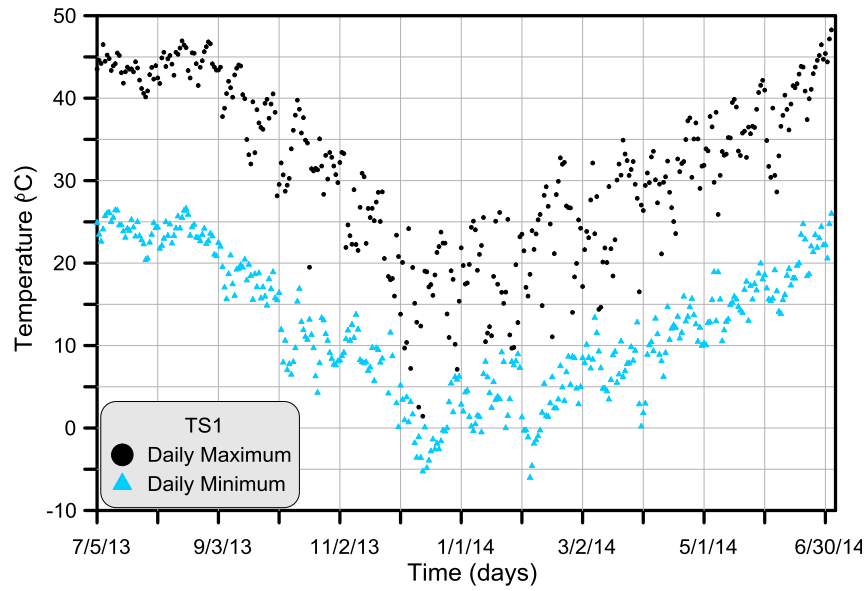


Figure 4.25 Daily maximum and daily minimum temperatures of thermocouple TS1 from July 2013 to July 2014

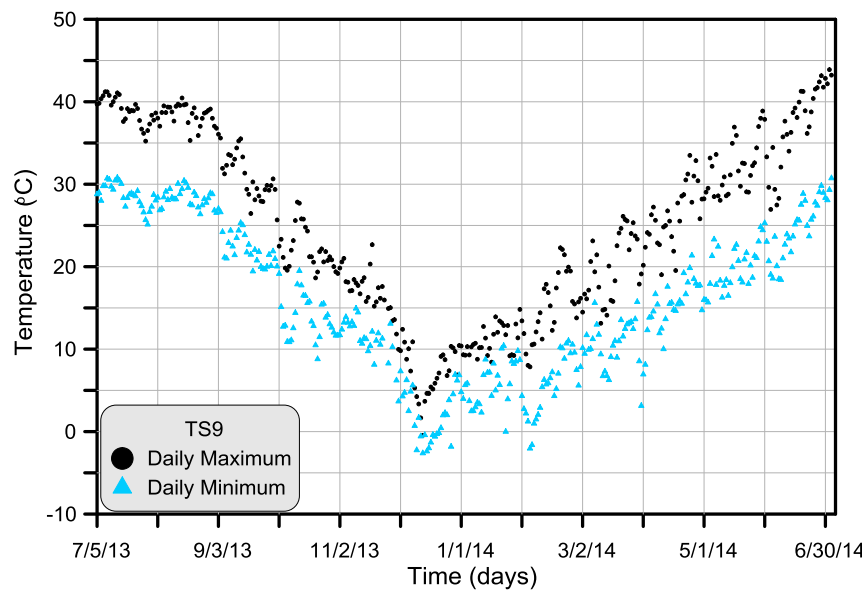


Figure 4.26 Daily maximum and daily minimum temperatures of thermocouple TS9 from July 2013 to July 2014

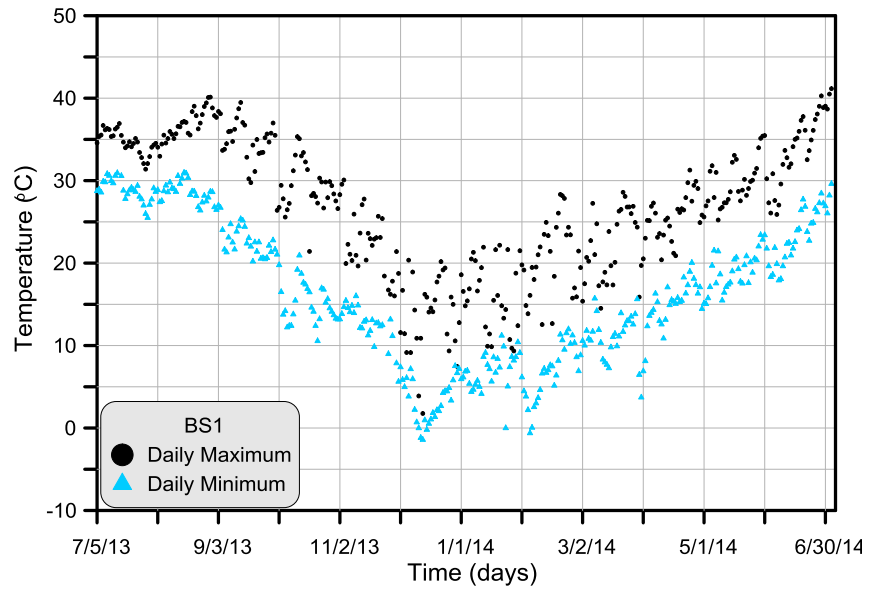


Figure 4.27 Daily maximum and daily minimum temperatures of thermocouple BS1 from July 2013 to July 2014

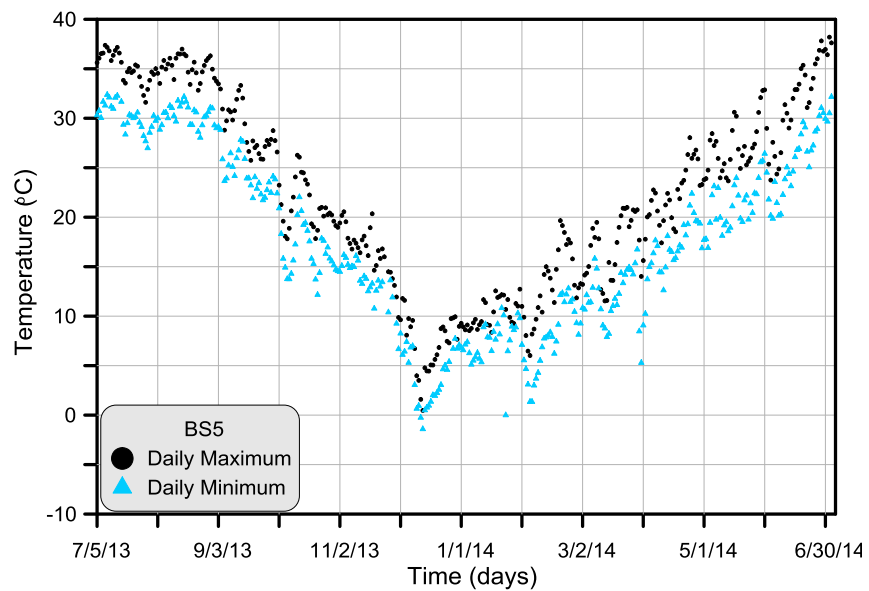


Figure 4.28 Daily maximum and daily minimum temperatures of thermocouple BS5 from July 2013 to July 2014

4.5 Vertical and Lateral Temperature Gradients

Figures 4.29 to 4.31 show the maximum daily vertical and lateral temperature gradients calculated for a complete one year for the period extended from 4-July-2013 to 3-July-2014. The temperature gradients were calculated by subtracting the minimum temperature from the temperatures of all thermocouples along the specified section. The sections along which the temperature distributions and temperature gradients were calculated are the centerlines of the webs from top slab to bottom slab (for vertical temperature distributions and gradients), while sections were taken along the centerlines of the top and the bottom slabs for lateral temperature distributions and gradients (from south edge to north edge).

Figure 4.29 shows that the maximum vertical temperature gradients were high during summer and decreased during autumn to reach minimum values during the winter. The temperature gradients became then higher during the spring season and reached maximum values again during the next summer. The maximum vertical gradients were recorded during hot summer days with high solar radiations and high differences between the daily maximum and minimum air temperatures.

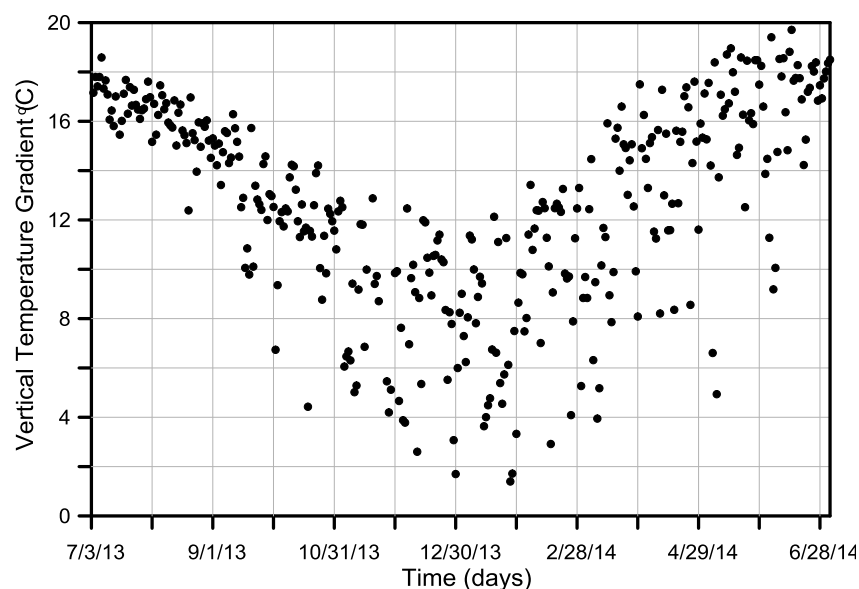


Figure 4.29 Daily maximum vertical temperature gradients along the centerline of the webs from July 2013 to July 2014

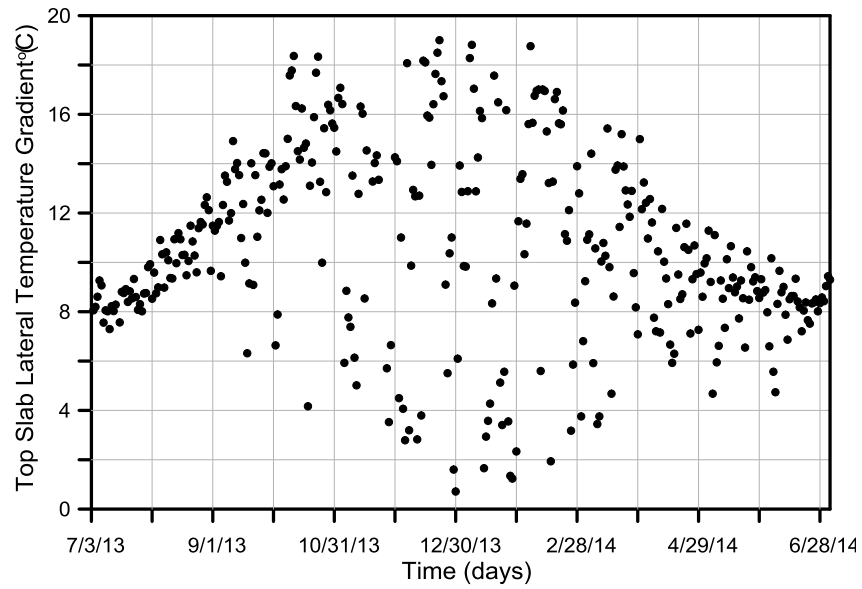


Figure 4.30 Daily maximum lateral temperature gradients along the centerline of TS from July 2013 to July 2014

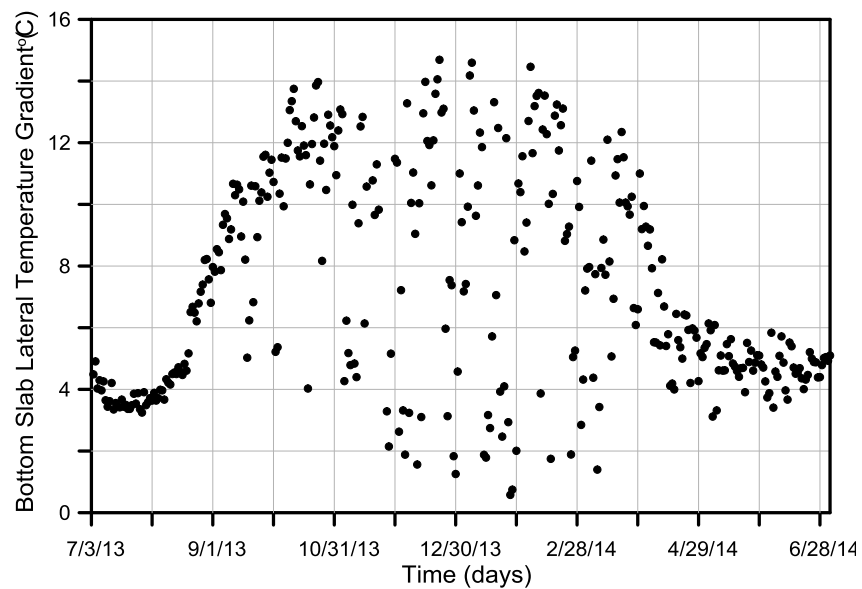


Figure 4.31 Daily maximum lateral temperature gradients along the centerline of BS from July 2013 to July 2014

Figures 4.30 and 4.31 show that the lateral temperature gradients were high during autumn and winter and low during summer. This is because sunrays during the cold seasons strike from low solar altitude angles, which leads to the heating of one edge of the horizontal members while the opposite edge is shaded. From the comparison

between the two figures, it is clear that top slab suffered higher lateral temperature gradients than bottom slab.

4.6 Results of Selected Days

The temperature distributions along the webs and the slabs at critical time steps, at which the maximum temperature gradients occur, are discussed in this section for selected days. Table 4.1 shows the essential thermal loads and the recorded maximum vertical and lateral temperature gradients. The presented days were those days with the maximum hourly solar radiation and the maximum daily air temperature difference along the four seasons of the year. In addition, the days with maximum-recorded vertical and lateral temperature gradients are presented. Moreover, an additional summer hot day was presented, which is 10-July-2013.

Table 4.1 Thermal loads and maximum vertical and lateral temperature gradients in selected days.

Day	Daily air temperature difference °C	Maximum hourly solar radiation W/m^2	Daily average wind speed m/s	Maximum vertical temperature gradient °C	Maximum lateral temperature gradient °C
10-Jul-2013	12.48	1035	2.26	17.66 (SW)	8.06 (TS)
18-Jul-2013	10.3	1162	2.55	16.02 (SW)	8.81 (TS)
6-Oct-2013	9.3	1038	1.4	11.74 (SW)	12.55 (TS)
11-Oct-2013	23.6	783	0.58	14.18 (SW)	18.37 (TS)
3-Dec-2013	14.1	796	0.93	7.63 (SW)	11.01 (TS)
22-Dec-2013	18.4	526	0.59	11.01 (SW)	19.0 (TS)
22-Mar-2014	18.6	821	0.6	16.6 (SW)	15.2 (TS)
16-Apr-2014	9.2	1129	1.07	12.66 (SW)	5.93 (TS)
10-Jun-2014	19.2	973	1.23	18.56 (SW)	9.01 (TS)
14-Jun-2014	16.6	1015	0.96	19.71 (SW)	8.39 (TS)

4.6.1 Maximum Vertical and Lateral Temperature Distributions

Figure 4.32 shows the maximum vertical temperature distributions in the selected days, which were all recorded along the south web. The presented distributions are termed as "maximum distributions" because from which the maximum vertical temperature gradients are derived.

It is clear in the figure, that the average web temperature was higher in the hot days, thus for 10-July, 18-July, 10-June, and 14-Jun than in other days, while the lowest average temperatures were recorded in December. The spring and autumn distributions seem to have close average web temperatures as shown in the distributions of 6-October, 11-October, 22-March, and 16-April.

The temperature distributions of the hot days show steeper temperature variation along the depth of the top slab. The temperature decreases from the highest temperature at the top slab sharply to the lower end of the web-slab's junction, thus about 0.4 m below the top surface, then followed by a mode of temperature stabilization along the net depth of the web (from the top slab's junction to the bottom slab's junction). Along the depth of the bottom slab, a minor temperature increase occurs as shown in Figure 4.32.

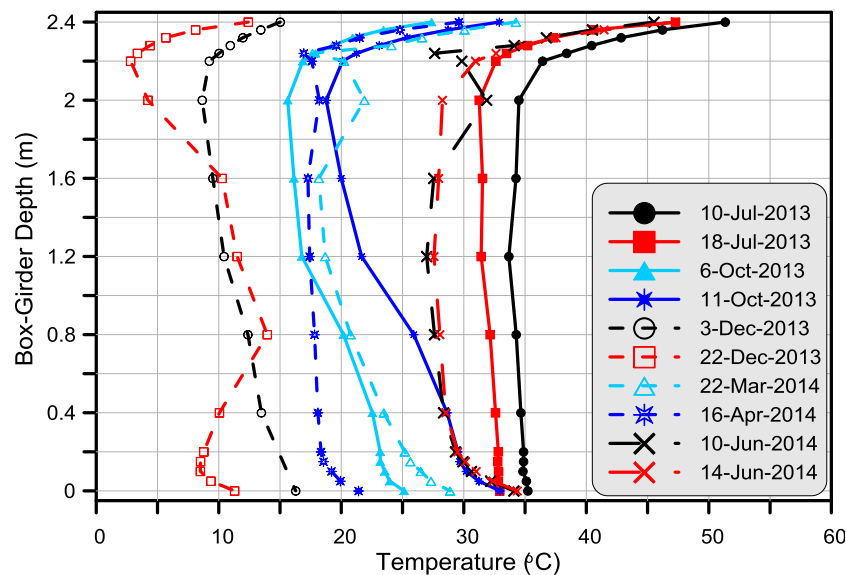


Figure 4.32 Maximum recorded vertical temperature distributions in the selected days

The distributions of October and March show lower temperature variation across the top slab. Another notice is that the region of stable or semi-constant temperature along the web seems to be shorter from the top slab's junction to about the mid height of the web. Below the mid height of the web, the temperature starts to increase gradually down to the bottom surface of the bottom slab. The temperature at the bottom surface is significant compared to the top surface's temperature.

The temperature distributions of winter (December) show much lower temperature variation across the top slab compared to those of hot days. In addition, the temperature difference between the top surface and the bottom surface is low as shown Figure 4.32.

Figure 4.33 shows the temperature distributions along the top slab in the selected days and at the time steps where the maximum lateral gradients occur. As discussed in Figure 4.32, Figure 4.33 shows that the average temperatures of the slab were much higher in summer than in winter or even in spring and autumn.

Two important notes can be drawn from Figure 4.33. The first is that for all days, the temperature is almost stable along the interior width of the slab (between webs), while the significant temperature variations occur along the south and the north cantilevers.

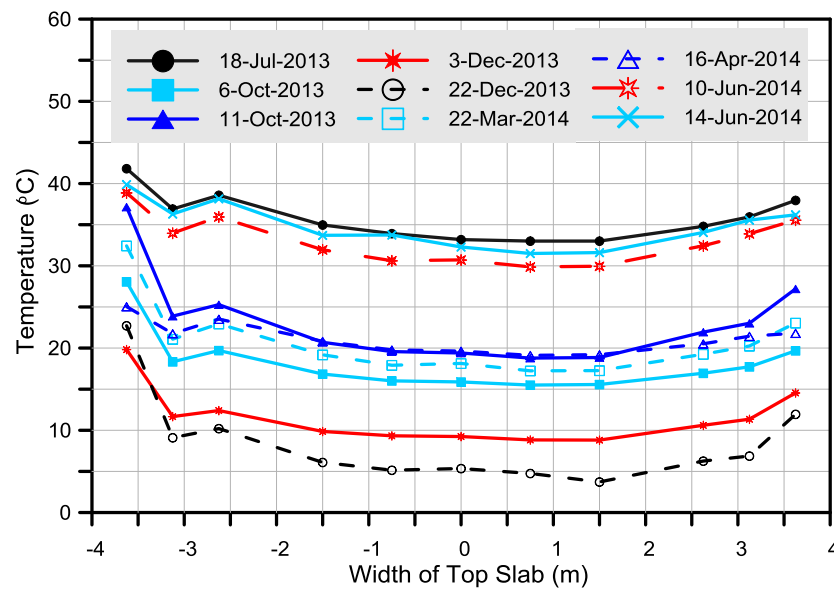


Figure 4.33 Maximum recorded lateral temperature distributions in the selected days

The second note is that the maximum temperature variations occur always at the southern edge of the slab and that it is much higher in winter (December) and autumn (October) than in summer (June and July) as shown in Figure 4.33 and listed in Table 4.1 (maximum lateral gradients).

4.6.2 Daily Variation of the Vertical and Lateral Temperature Gradients

To visualize more-detailed results, three days from the selected 10 days that are listed in Table 1 were elected, these three days are 22-December, 22-March, and 14-June. Figures 4.34 through 4.36 show the 24 hours variation of the temperature gradients along the top slab, the bottom slab, the south web, and the north web. Figure 4.34 shows the variation of the four temperature gradients in 22-December. It is clearly shown in the figure that the lateral gradients and their variations were much higher than vertical gradients. During the night hours, the vertical gradient along the south web was the maximum, while during the day hours, lateral gradients (TS and BS) showed much more increase than vertical gradients (SW and NW). This is due to the higher solar intensity on vertical surfaces than on horizontal surfaces in winter. The recorded maximum gradients along TS, BS, SW, and NW were 19°C, 15.1°C, 11.1°C, and 7.7°C, respectively.

In March, the solar radiation on horizontal surfaces is generally higher than on vertical surface. However, the difference between them is not so significant. Figure 4.35 shows the variation of the vertical and lateral temperature gradients in 22-March. It is clear that all gradients showed similar behavior of variation with time, and that the maximum gradients were close to each other's. Depending on the solar radiation distribution on horizontal and vertical surfaces, the maximum vertical gradients were slightly higher than the maximum lateral gradients. The recorded maximum gradients along TS, BS, SW, and NW were 15.2°C, 11.5°C, 16.6°C, and 15.4°C, respectively.

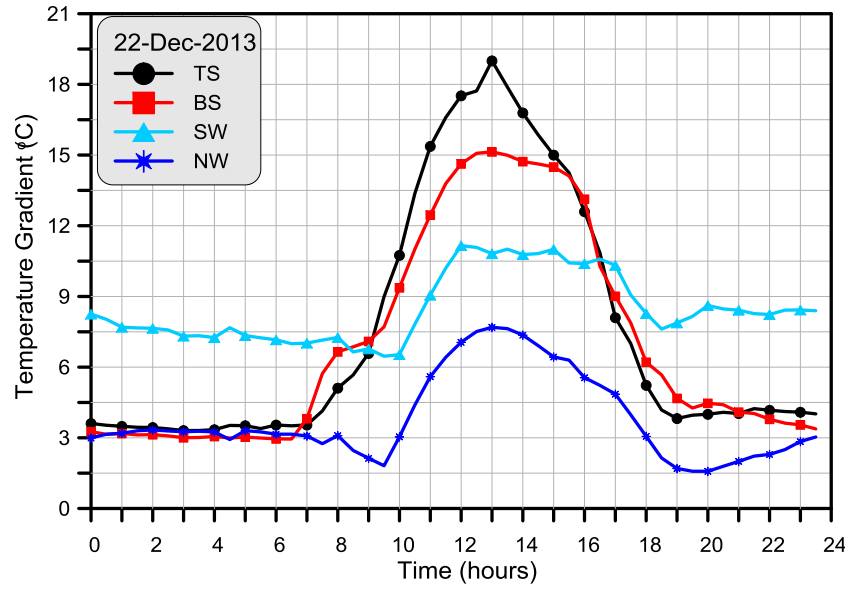


Figure 4.34 Temperature gradient-time variations in 22-December

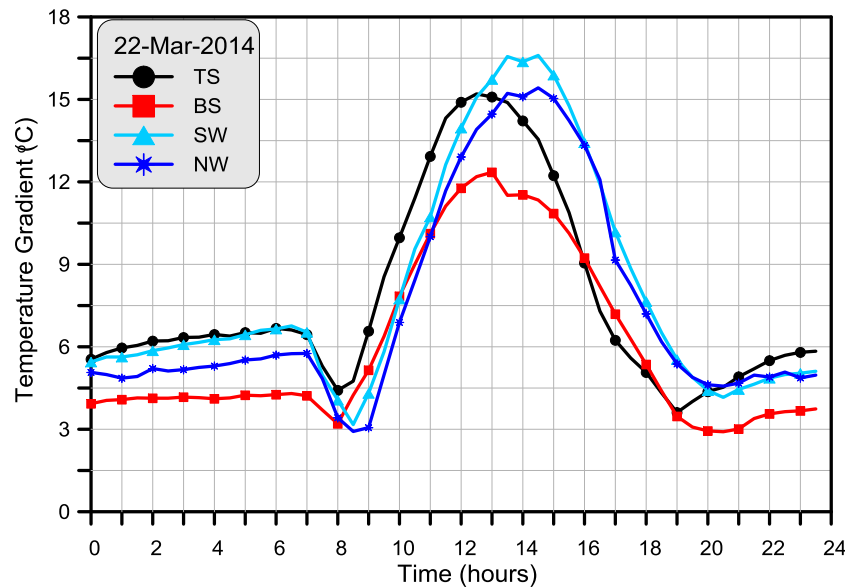


Figure 4.35 Temperature gradient-time variations in 22-March

Figure 4.36 shows that the gradient variations in 14-June are in contrast to those in 22-December. The vertical temperature gradients were much higher than the lateral gradients, which is simply can be attributed to the much higher solar radiation on horizontal surfaces compared to on vertical surfaces in June. The recorded maximum gradients along TS, BS, SW, and NW were 8.4°C, 5.4°C, 19.7°C, and 17.4°C, respectively.

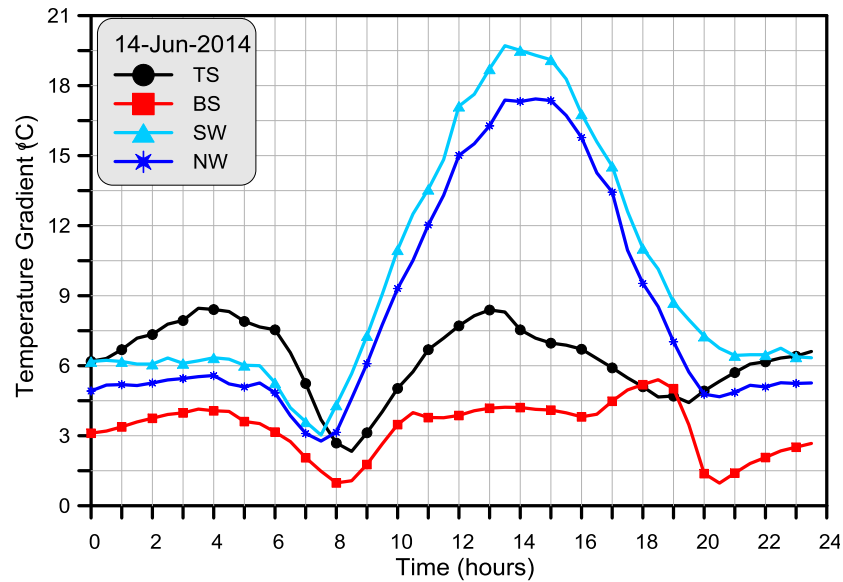


Figure 4.36 Temperature gradient-time variations in 14-June

4.6.3 Vertical and Lateral Temperature Distributions in the Selected Days

For the same three elected days (22-December-2013, 22-March-2014, and 14-June-2014), the vertical distributions along SW and NW in addition to the lateral distributions along TS and BS are visualized for selected time steps. The presented time steps are 3:00 AM, 6:00 AM, 9:00 AM, 12:00 PM, 3:00 PM, and 6:00 PM. Figures 4.37 through 4.40 show the vertical and the lateral temperature distributions in 22-December. On the other hand, Figures 4.41 through 4.44 show the distributions in 22-March, while Figures 4.45 to 4.48 show the temperature distributions in 14-June.

Figure 4.37 shows the vertical temperature distributions along SW. It is shown that solar radiation has almost equivalent effect on both the top horizontal surface and the south web's vertical surface. In winter, sun rises from the southeast, moves to the south of the zenith, and set at the southwest. Thus, solar affects the southern surfaces of the girder, while the northern surfaces are completely shaded. This explains why the temperature of the webs (especially nears mid-height) are as high as the temperatures of the top surface during the day hours as shown in Figure 3.37. The recorded temperatures at the top surface at 12:00 PM and 3:00 PM were 12.4°C and

15.2°C, while their corresponding temperatures at 1.6 m below the top surface were 14°C and 17.1°C.

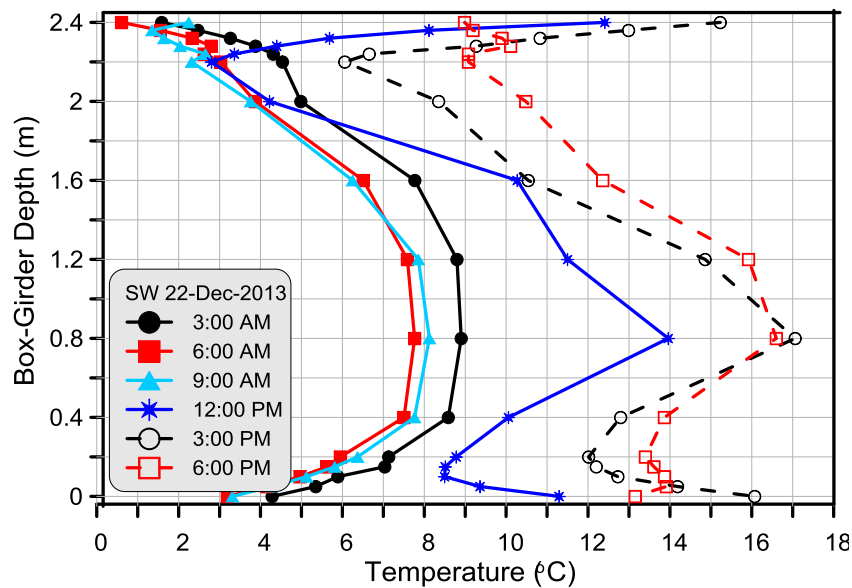


Figure 4.37 Vertical temperature distributions along SW at different time steps in 22-December

At the same time steps, the temperatures at the bottom surface were as significant as the temperatures at the top surface, where the temperatures at 12:00 PM and 3:00 PM at the bottom surface were 11.3°C and 16.3°C. On the other hand, the temperatures of the web kept high during the night hours compared to the temperatures of the top surface and the bottom surface thermocouples as shown in Figure 4.37.

Figure 4.38 shows that the temperature distributions along NW are much stable along the clear height of the web than along SW, which is attributed to the stabilized shading effect, hence the limited solar radiation effect on the north web during the day hours. The effect of solar radiation on the top and on the bottom surfaces still close as that of the south web. The temperatures of the top surface thermocouple (NW1) at 12:00 PM and 3:00 PM were 9.8°C and 11.7°C, while the corresponding temperatures were 6.7°C and 10.4°C at the bottom surface (NW18). During the night hours, the temperature of the web decreased but still semi-uniform along the mid-

height of the web, while the temperature at the top and bottom surfaces decreased noticeably due to the convection cooling and the surface re-radiation.

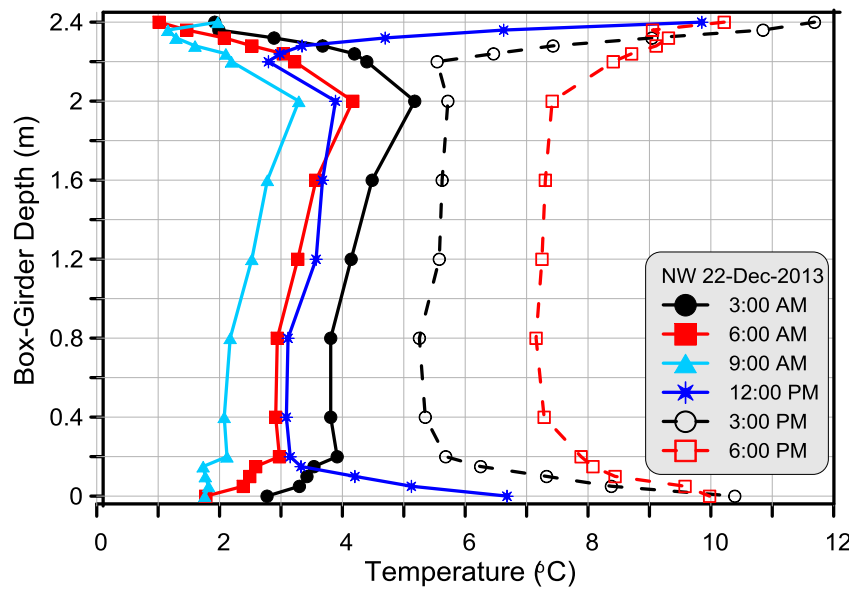


Figure 4.38 Vertical temperature distributions along NW at different time steps in 22-December

Figures 4.39 and 4.40 show that almost at all time steps, the temperature was semi-uniform along the interior width of the slabs, while the temperature of the edges were higher during the day and lower during the night. Since the effect of solar radiation on the southern surfaces is much higher than on the northern surfaces, the maximum temperatures occurred at the southern edges of TS and BS. It is clear in the figures that among the visualized time steps, the maximum temperature jump of the southern thermocouples (TS1 and BS1) compared to the interior thermocouples occurred at 12:00 PM. It is also noticed that the temperature distributions along the bottom slab were more stable than along the top slab, which can be attributed to the lower effect of solar radiation on the bottom slab compared to the top slab.

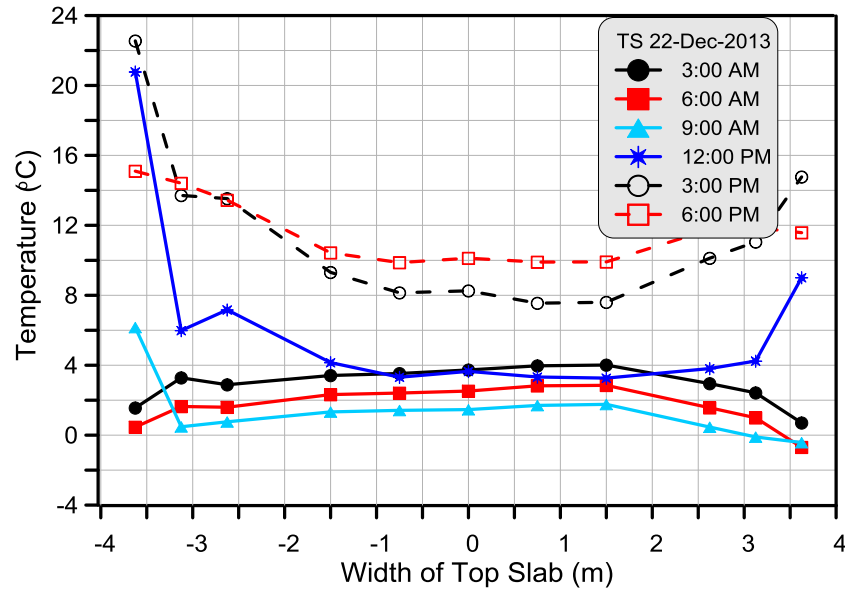


Figure 4.39 Lateral temperature distributions along TS at different time steps in 22-December

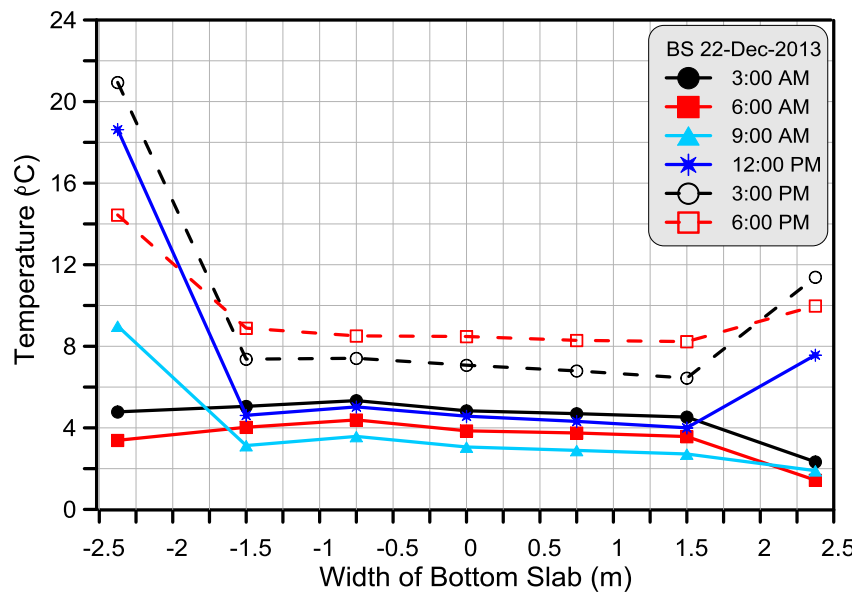


Figure 4.40 Lateral temperature distributions along BS at different time steps in 22-December

Figures 4.41 to 4.44 show the vertical and lateral temperature distributions in 22-March. It is shown in Figures 4.41 and 4.42 that the temperature distributions are more stable along the mid-height of the north web than along the south web, which was discussed in the vertical distributions of 22-December. However, comparing the

temperature distributions along SW of 22-December and 22-March, the temperature along the mid-height of the web is more stable in 22-March than in 22-December as shown in Figure 4.41.

In March, the sun rises from the east and sets at the west, but it also moves to the south of the zenith. Thus, solar radiation affects the southern surfaces much more than the northern surface, however, this effect is less than in winter. Note that the zenith angle at the noon of 22-March in Gaziantep is about 40° , while it is about 59° at the noon of December. Thus, the solar radiation effect on vertical surfaces is more than on horizontal surfaces in December, while it is higher on horizontal surfaces in March. This explains the more temperature uniformity along the mid-height of SW in 22-March compared to 22-December.

Similar to the vertical temperature differences in 22-December, the difference between the maximum temperatures at the bottom surface and those at the top surface of SW is not high. The recorded temperatures at 12:00 PM and 3:00 PM at the top surface along the south web (SW1) were 29.6 and 34°C, while the recorded temperatures at SW18 were 26°C and 29°C. However, the temperature of NW18 was much lower than NW1, while it was not so in 22-December. This can be again attributed to the lower zenith angle of the sun during 22-March compared to 22-December, which leads to less effect of solar radiation on the bottom surface at the northern edge.

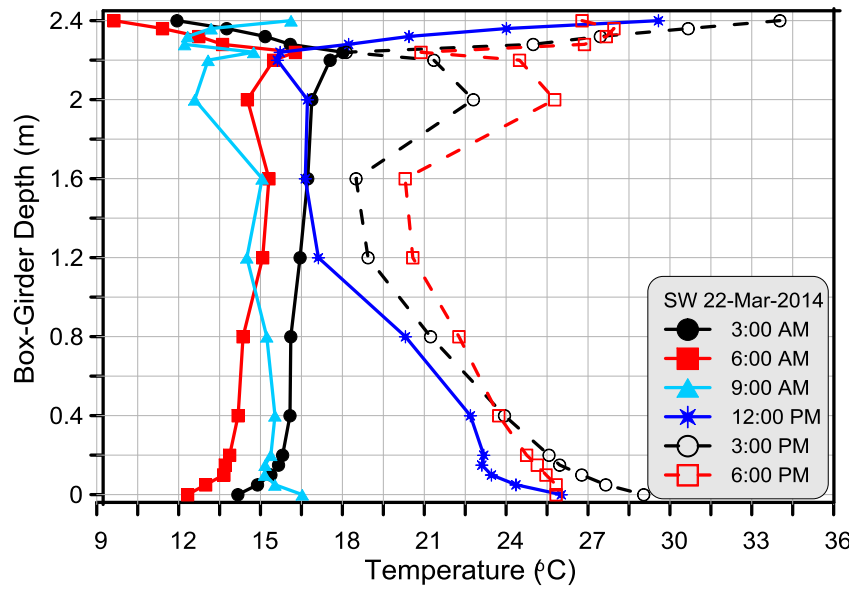


Figure 4.41 Vertical temperature distributions along SW at different time steps in 22-March

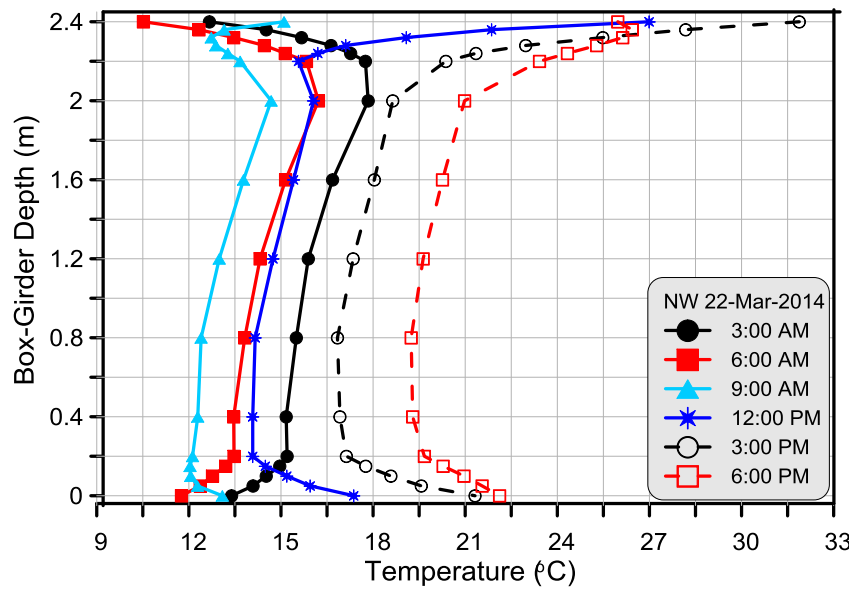


Figure 4.42 Vertical temperature distributions along NW at different time steps in 22-March

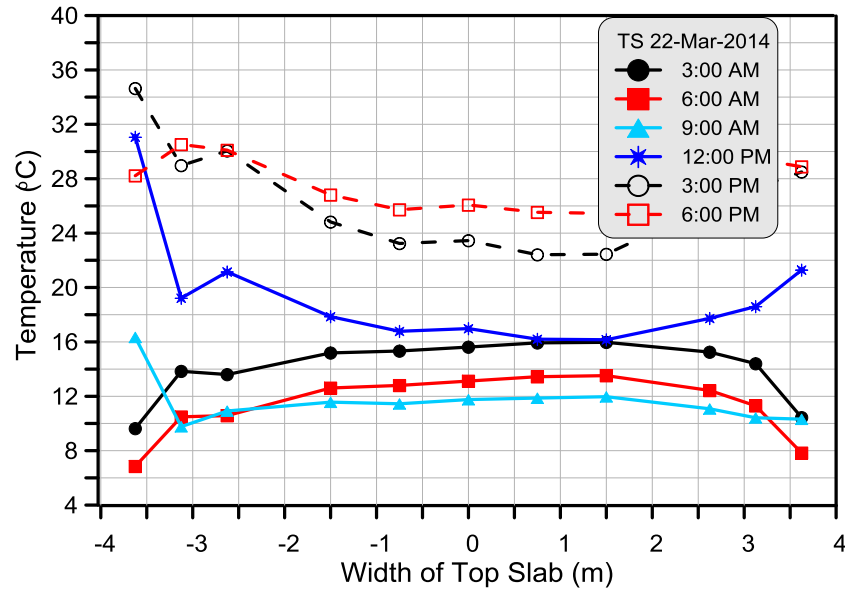


Figure 4.43 Lateral temperature distributions along TS at different time steps in 22-March

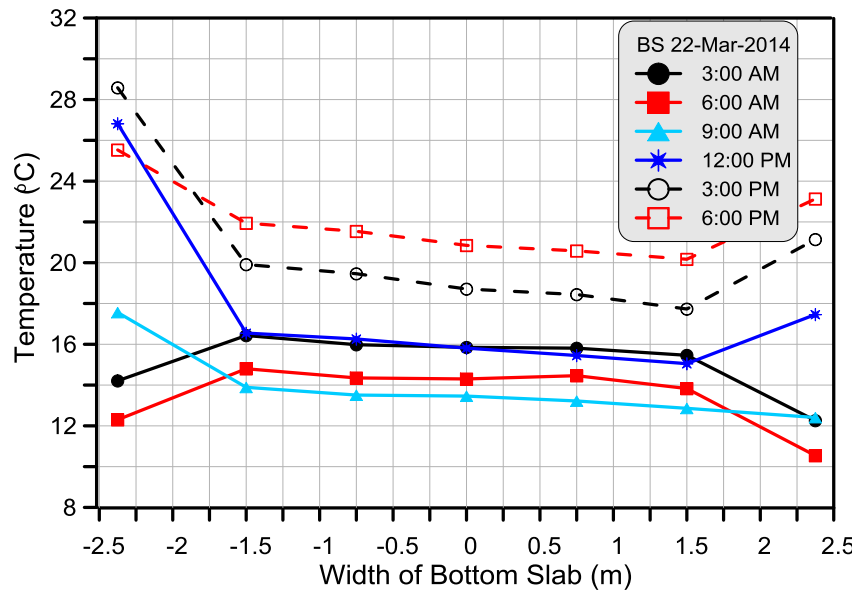


Figure 4.44 Lateral temperature distributions along BS at different time steps in 22-March

Comparing the temperature distribution along TS in 22-March, which is shown in Figure 4.43 with that in 22-December and the temperature distribution along BS in 22-March (Figure 4.44) with that in 22-December (Figure 4.40), the same notices can be drawn. However, the temperature jumps at the southern edge were lower in

22-March. The recorded difference between the temperatures of TS1 and TS3 (the adjacent thermocouple) at 12:00 PM (which is the maximum) was 11.8°C in 22-March, while it was 14.8°C in 22-December. Similarly, the temperature difference between BS1 and BS2 at 12:00 PM was 10.3°C in 22-March, while it was 14°C in 22-December.

For design purposes, the vertical temperature distributions in 14-June are more important than the temperature distributions in 22-December and 22-March. The vertical temperature gradients are much higher in summer than in winter or spring and autumn, therefore, the design gradients are modeled for summer conditions in all of the bridge design codes.

In June, the sun rises from the northeast moving towards the south, crossing the east-west- zenith plane about 3 hours before the noon, at which the sun is at the highest altitude in the sky with about zero zenith angle. This movement is then reversed, from south to north, reaching the sunset at the northwest. Thus, solar radiation on horizontal surfaces is much higher than on vertical surface. It can also be concluded that solar radiation on the north web is also significant.

Due to the above explanations, the solar radiation increases the temperature of the top surface (hence the top thermocouples SW1 and NW1) noticeably during the day hours and especially from about 10:00 AM to about 5:00 PM. Thus, leading to much higher temperature at the top surface compared to the rest thermocouples during the day hours. Figures 4.45 for the south web and 4.46 for the north web clearly illustrate that the temperatures at the top surface are much higher than the temperatures along the interior depth of the webs, which results in higher temperature gradients. The temperatures at the top surface of SW at 12:00 PM and 3:00 PM were 43.5°C and 47.5°C, while the temperatures at the mid-height of the web were 26.4°C and 28.34°C at the same time steps as shown in Figure 4.45. Similarly, and as shown in Figure 4.46, the temperatures at the top surface of NW at 12:00 PM and 3:00 PM were 40.7°C and 45.2°C, while the temperatures at the mid-height of the web were 26.2°C and 28.3°C.

Another difference between the vertical distribution of June and those in winter and spring is that due to the high altitude of the sun, it has lower effect on the bottom

surface compared to the top surface. The temperatures at the bottom surface at 12:00 PM and 3:00 PM were 33°C and 35.2°C for SW, while they were 29.3°C and 32.5°C for NW.

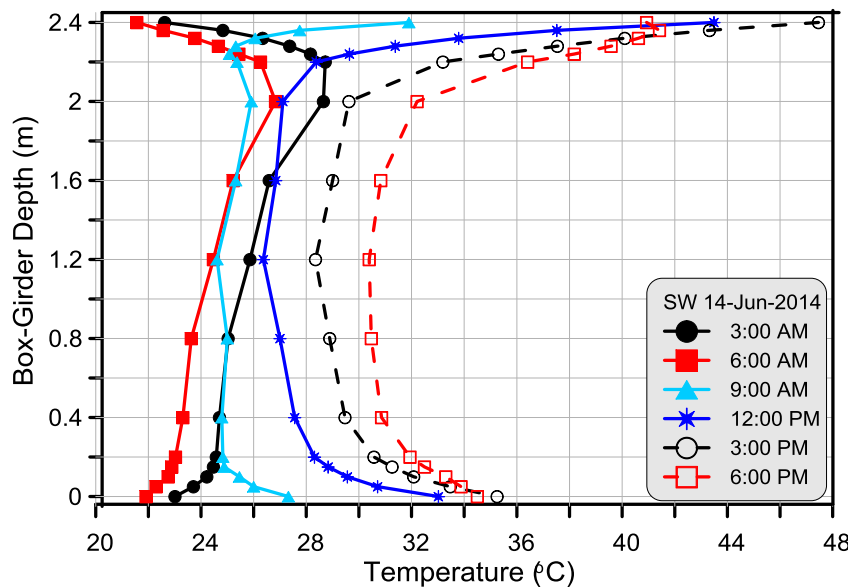


Figure 4.45 Vertical temperature distributions along SW at different time steps in 14-June

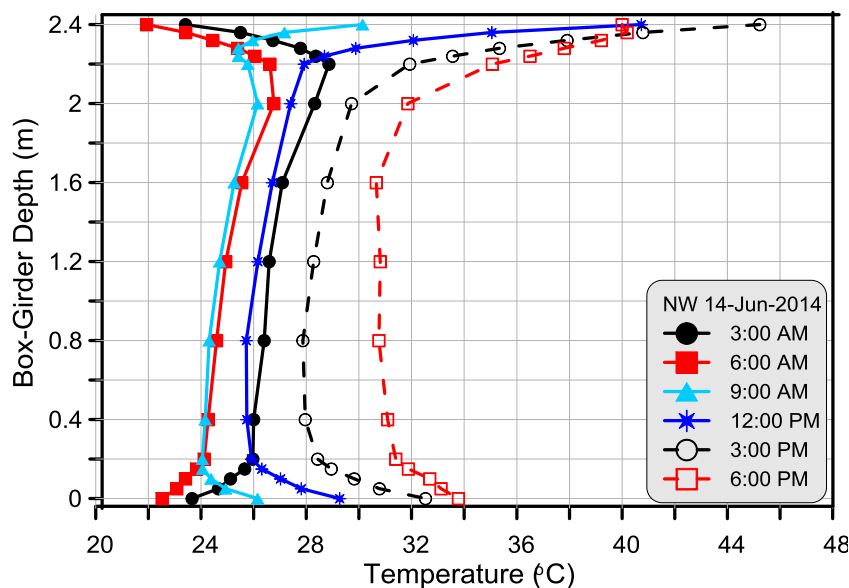


Figure 4.46 Vertical temperature distributions along NW at different time steps in 14-June

The vertical temperature distributions during the night hours show that as in winter and in spring, the temperatures of the top and the bottom surfaces decreases noticeably to be lower than those along the interior depth of the webs as shown in Figures 4.45 and 4.46.

Figures 4.47 and 4.48 show that the temperature distributions along the interior widths of the top and bottom slabs have lower uniformity compared to the same distributions in December and March. In addition, the temperature jump at the southern edge is lower than that in December and March. Thus, the lateral temperature gradients are much lower in June. Moreover, it can be seen that due to the sun movement from the northern surfaces (at sunrise) to the southern surfaces and then to the northern surfaces back at sunset, temperature jumps occurred at the northern edges. At the time steps close to the sunrise and the sunset (at 6:00 AM and 6:00 PM), the temperature of the northern edge thermocouples (TS17 and BS9) were higher than those at the southern edges (TS1 and BS1), which is clearly illustrated in Figure 4.47 for the top slab and Figure 4.48 for the bottom slab.

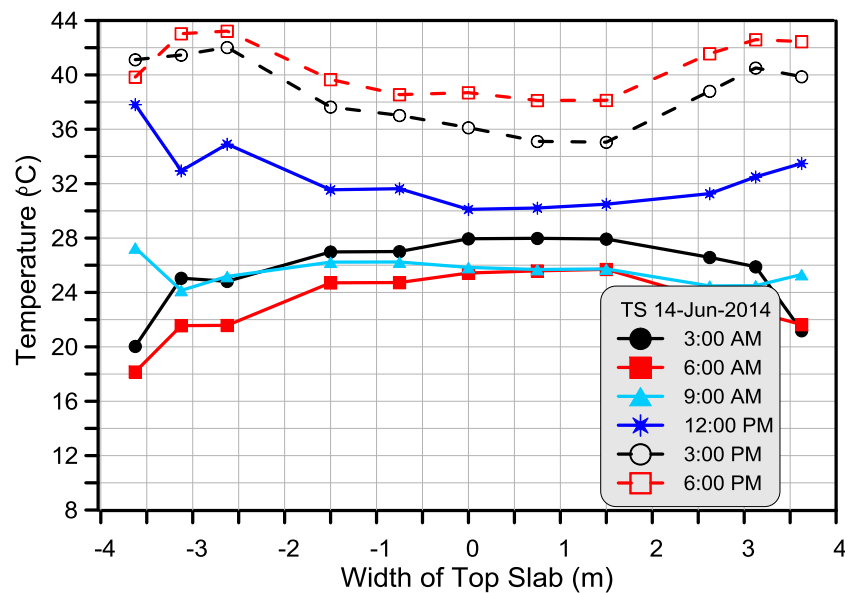


Figure 4.47 Lateral temperature distributions along TS at different time steps in 14-June

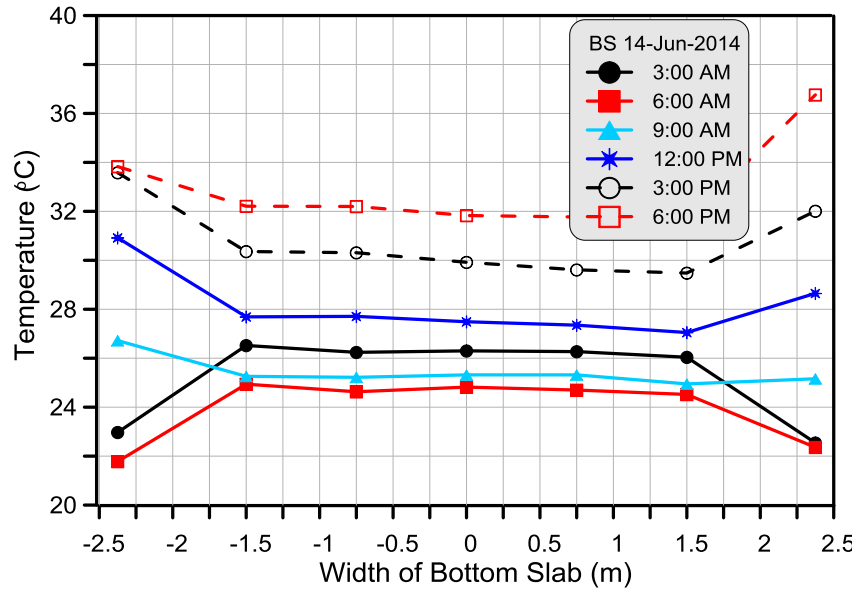


Figure 4.48 Lateral temperature distributions along BS at different time steps in 14-June

4.7 Mean Temperature of the Box-Girder

In the design of thermal actions in bridges, the maximum and minimum mean temperatures of the bridge are required to calculate the longitudinal thermal movements. The mean temperature of the bridge is the average of the individual temperatures of the different parts of the superstructure.

In the current experimental work, 62 thermocouples were distributed as described in Table 3.3 and Figures 3.15 and 3.16 in chapter 3. The mean temperature of the box-girder was estimated at each time step by calculating the sum of the products of each thermocouple by its surrounding area measured to the centerlines of the adjacent thermocouples (horizontally and vertically). The summation of the products is then divided by the total area of the box-girder. The mean temperature is thus calculated by:

$$MT = \sum T_i A_i / \sum A_i \quad (4.1)$$

Where T_i is the temperature of the thermocouple i at the time step under consideration, and A_i is the individual area that surrounds the thermocouple i

measured to the centerlines of the distances to the adjacent thermocouples distributed horizontally and vertically.

Figure 4.49 shows the daily maximum mean temperature of the box-girder from 4-July-2013 to 3-July-2014, while Figure 4.50 shows the daily minimum mean temperature for the same period. By the Comparison with Figures 4.1 and 4.2 for the daily maximum and daily minimum air temperatures, it is shown that the mean temperature of the box-girder is highly correlated to air temperature.

For the period from 4-July-2013 to 3-July-2014, the daily maximum mean temperature ranged from 4.9 °C to 41.3 °C. On the other hand, the daily minimum mean temperature of the box-girder ranged from -2.0 °C to 31.4 °C.

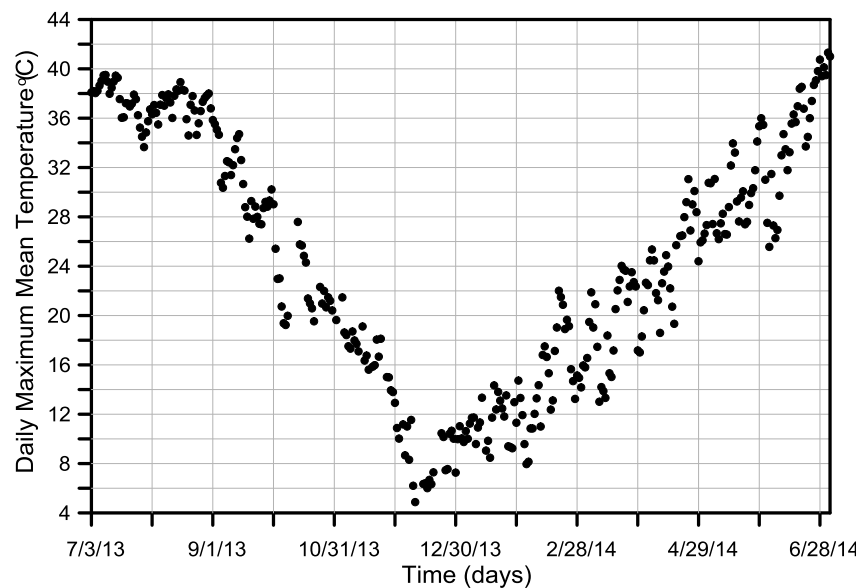


Figure 4.49 Daily maximum mean temperature of the box-girder for the period from 4-July-2013 to 3-July-2014

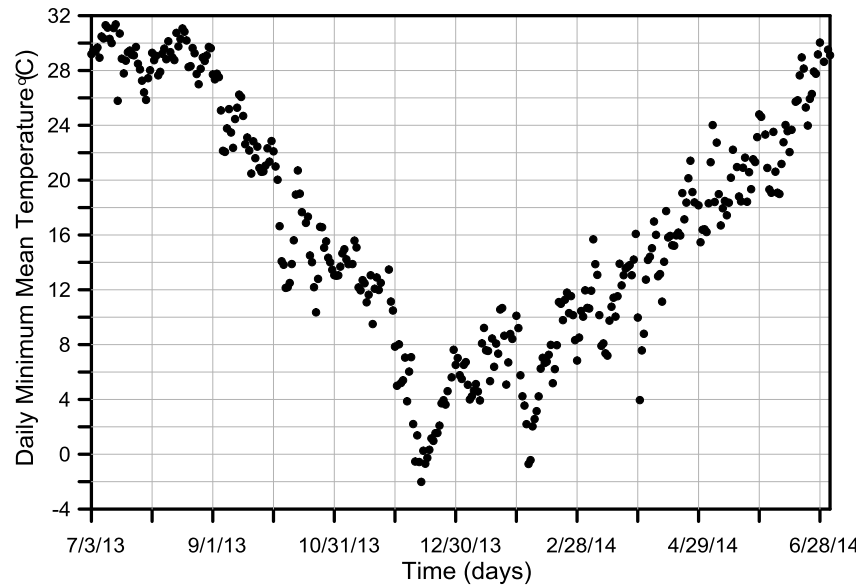


Figure 4.50 Daily minimum mean temperature of the box-girder for the period from 4-July-2013 to 3-July-2014

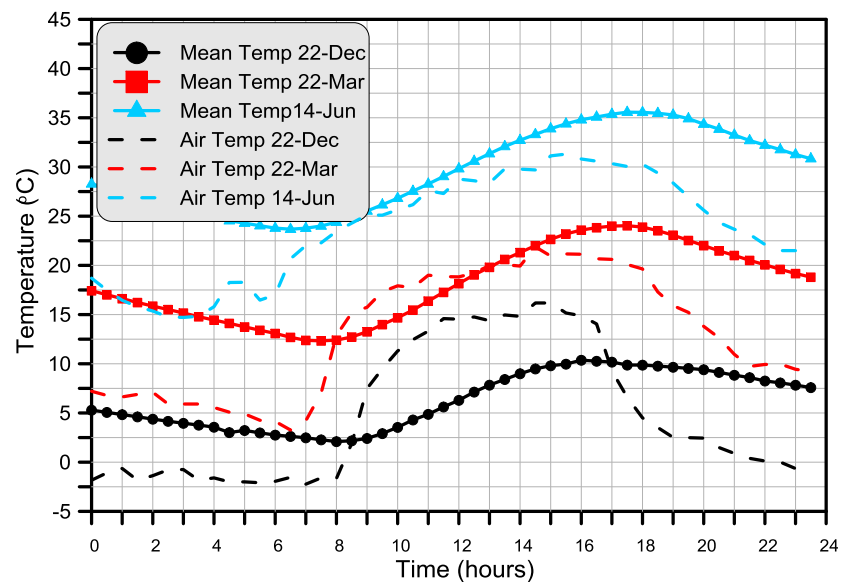


Figure 4.51 Mean temperature of the box-girder and air temperature during the 24 hours of selected days

Figure 4.51 compares the mean temperature of the box-girder during the 24 hours of three selected days (22-December-2013, 22-March-2014, and 14-June-2014) with air temperature in the same days. The Figure shows that air temperature have an

obvious impact on the mean temperature of the box-girder, where the inflection points and the regions of increase and decrease are similar.

4.8 Temperature of Air inside the Box-Girder

As discussed in chapter three, isolation boards were used to seal the box cavity in the longitudinal axis, which simulates the real box-girders where no air or light are allowed to flow inside the box cavity. The temperature inside the box-girder was calculated at each time step using two thermocouples. The thermocouples were installed near the interior surfaces of the southern and northern webs. The temperature of the inside-box was considered as the average temperature of the two thermocouples. The measurements of the two thermocouples were started in July-2013 and continued to July-2014.

Figure 4.52 shows the variation of the average temperature of the air inside the box-girder from 13-July-2013 to 3-July-2014, while Figures 4.53 and 4.54 show the variation of the maximum and minimum temperatures of the air inside the box during the same period. It is clear that the temperature of the air inside the box is highly affected by the ambient air temperature where Figures 4.53 and 4.54 show high dependency on Figures 4.1 and 4.2.

Figure 4.55 shows the comparison between the temperatures of the air inside the box with that of the ambient air for three selected days. The figure reflects the high effect of the ambient air temperature on the behavior of the in-box air curves during the 24 hours of the three days.

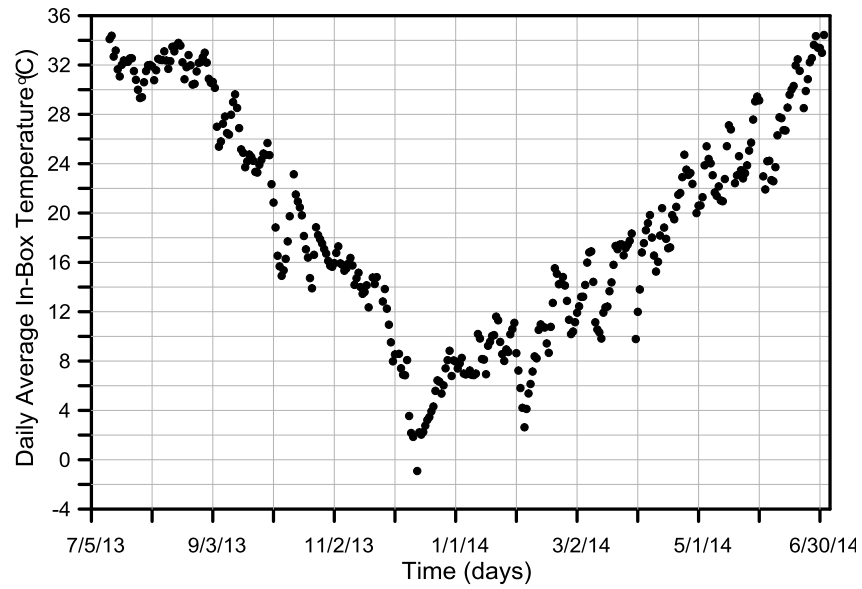


Figure 4.52 Daily average of air temperature inside the box-girder for the period from July-2013 to July-2014

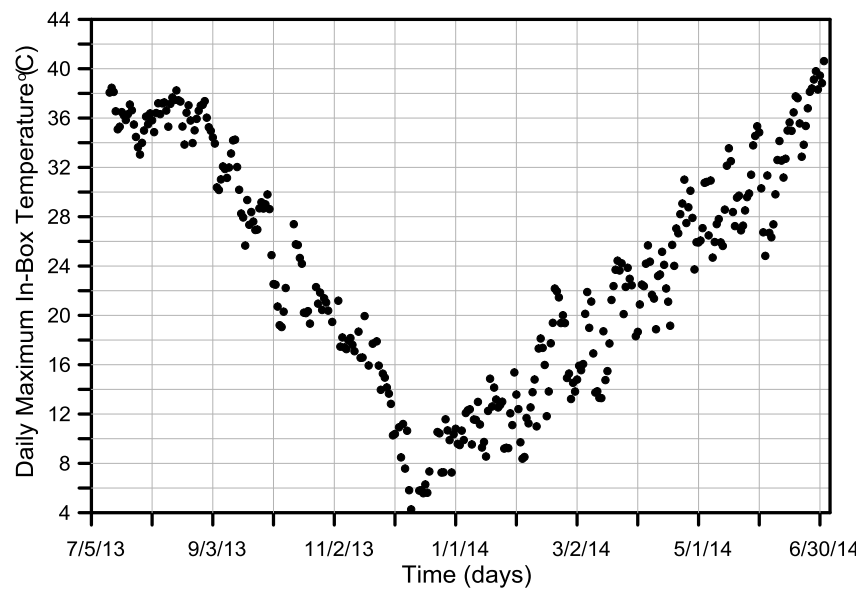


Figure 4.53 Daily maximum of air temperature inside the box-girder for the period from July-2013 to July-2014

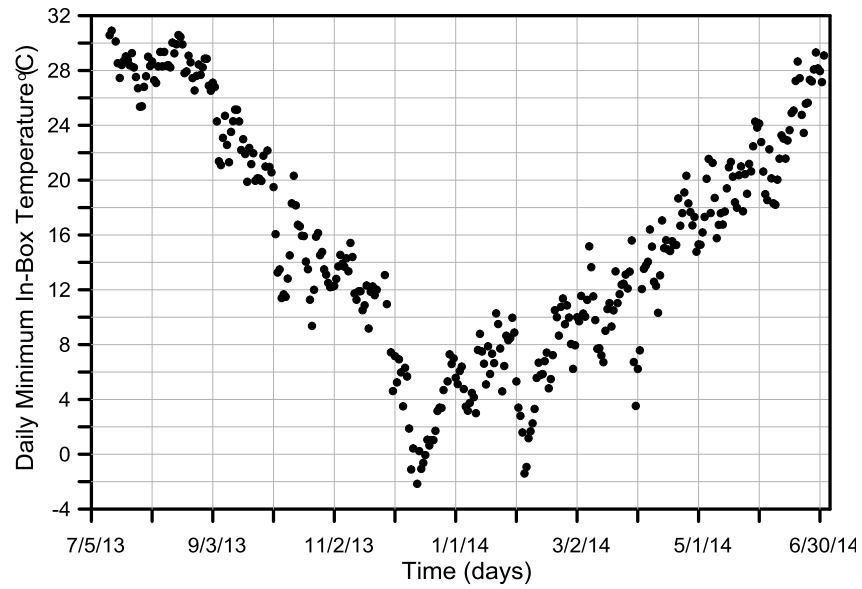


Figure 4.54 Daily minimum of air temperature inside the box-girder for the period from July-2013 to July-2014

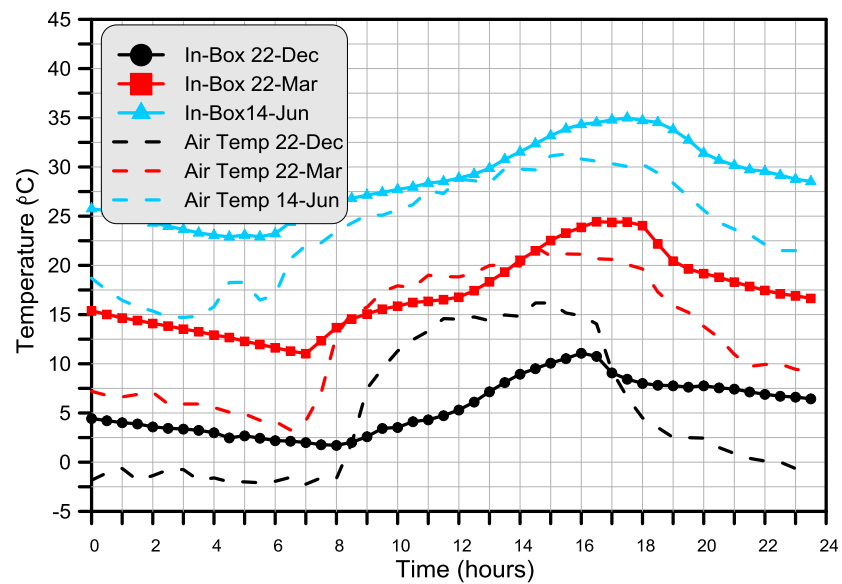


Figure 4.55 Temperature of air inside the box-girder and air temperature during the 24 hours of selected days

CHAPTER FIVE

STATISTICAL ANALYSIS OF THE EXPERIMENTAL RESULTS

5.1 General

In this chapter, the experimental measurements from the thermocouples and the weather station are used to study the relationships between the environmental thermal loads and the vertical and lateral temperature gradients. In addition, the correlations of the effective thermal loads and the bridge's mean temperature are analyzed and discussed. Moreover, in this chapter, the effects of the ambient air temperature on the temperature of air inside the box-girder are statistically analyzed.

The maximum temperature gradient at the top surface of a concrete box-girder can be evaluated for any location and any weather conditions using the regression formulas obtained based on the experimental measurements of the current study. Similarly, the maximum lateral temperature gradients at the edges of the top and the bottom slabs for any box-girder bridge under any weather conditions can be evaluated using the correlation relations of the lateral gradients discussed in this chapter.

Three statistical measurements were used to evaluate the degree of confidence on the predicted formulas, these are:

- The R-squared (R^2) or the coefficient of determination, which evaluates the degree of correlation between the predicted values and the test values by calculating for the sum of squares of residuals, where:

$$R^2 = 1 - \frac{\sum(X_{\text{test}} - X_{\text{pred}})^2}{\sum(X_{\text{test}} - \bar{X})^2} \quad (5.1)$$

Where X_{pred} is the predicted value, X_{test} is the corresponding test or experimental record at the same time step, $\bar{X}$ is the mean of n test records.

- The Average Absolute Error (AAE), which can be represented by Equation 5.2 and the Maximum Absolute Error (MaAE), which is the maximum recorded difference between the predicted and the experimental records among the whole set of data.

$$AAE = \frac{\sum |X_{pred} - X_{test}|}{n} \quad (5.2)$$

- The root-mean-square error (RMSE), which is the square root of the mean of squared errors between the predicted and the test values, and is given by:

$$RMSE = \sqrt{\frac{\sum (X_{pred} - X_{test})^2}{n}} \quad (5.3)$$

The concrete temperature records from the thermocouples in addition to air temperature, solar radiation, and wind speed records from the weather station for the period extended from 4-July-2013 to 3-July-2014 were used to find the formulas of this chapter. During the period extended from the last third of November to the first third of January, one of the multiplexers was affected by moisture and the readings of eight thermocouples were not correct in some days of this period. Some of these thermocouples were essential to calculate the vertical or lateral temperature gradients, and thus their readings were omitted from the correlation calculations. In addition, in some days the solar radiation was highly fluctuated due to the fluctuation of the cloud cover. The data of these days were also not considered in the calculations.

5.2 Vertical Temperature Gradient

The vertical gradients along the centerline of the webs were calculated as described in section 4.5 in chapter 4. The daily maximum vertical gradients for the period from 4-June-2013 to 3-June-2014 are shown in Figure 4.29. As explained above in section 5.2, some of these values were not included in the correlation calculations. In this section, the correlations with the daily air temperature difference (DT), the daily total solar radiation (I), and the daily average wind speed (w) are discussed. In addition, the predicted formula of the maximum vertical temperature gradient as a

function of all of the mentioned environmental thermal loads is presented and compared with other formulas from literature.

5.2.1 Correlations with Thermal Loads

Direct correlations were made between the daily maximum vertical gradient on the top surface of the box girder (Ver) and the daily difference of air temperature, which equals:

$$DT = T_{a,max} - T_{a,min} \quad (5.4)$$

The linear relation between DT and Ver has a low R^2 , which was 0.315. On the other hand, the second-degree polynomial gave better value of R^2 , which was 0.418, however, this value still low to depend on DT alone for the estimation of the daily maximum vertical gradient.

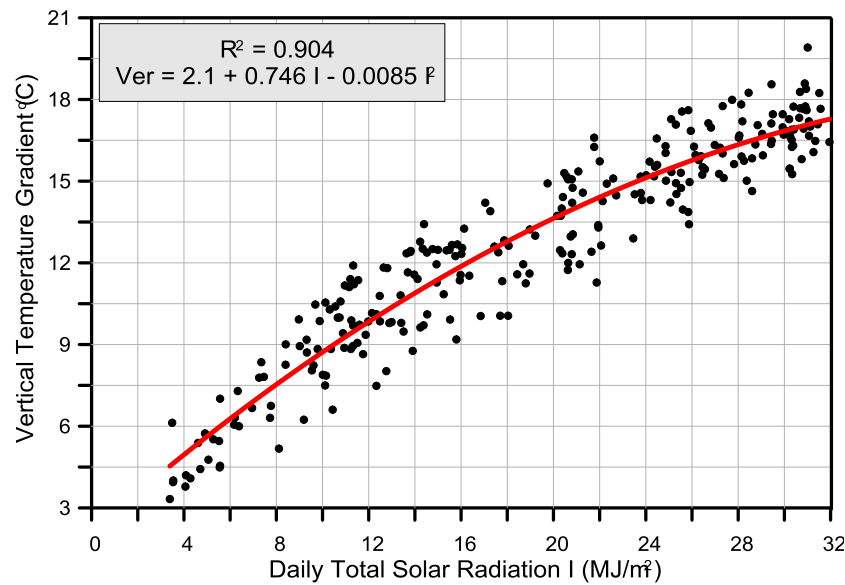


Figure 5.1 Daily maximum vertical temperature gradient vs daily total solar radiation

The daily maximum vertical temperature gradient was also correlated to the daily total solar radiation, which is the sum of the 24 hours of solar radiation in MJ/m^2 . The linear relation was very simple and the determination coefficient R^2 was quite good, which was 0.887, which means that the correlation coefficient R equals 0.942.

Figure 5.1 shows that the second-degree polynomial function resulted in higher R^2 , which was 0.904 ($R = 0.951$), this reveals that the daily maximum vertical gradient is highly correlated to the daily total solar radiation. Thus, the daily total solar radiation can be used with a good degree of confidence to evaluate the daily maximum vertical temperature gradient if the other parameters are absence for a selected location.

In the literature, predicted formulas to estimate the daily maximum vertical temperature gradients were found to include third and fourth degree terms of wind speed. Therefore, the daily average wind speed was tested in linear correlation in addition to second, third, and fourth degree polynomials. The R^2 was nearly the same for the four formulas and was less than 0.1, which discloses the limited effect of wind speed on the vertical gradient.

5.2.2 Predicted Vertical Gradient Formula

The discussion of the previous section showed that the daily maximum vertical gradient is highly correlated to solar radiation, and moderately correlated to air temperature, while its correlation with wind speed was weak.

As a primary step, a stepwise regression was conducted including the following variables:

- DT : the daily difference of air temperature in $^{\circ}\text{C}$
- $3DT$: the 3-day average of the daily difference of air temperature in $^{\circ}\text{C}$
- T_{max} : the daily maximum air temperature in $^{\circ}\text{C}$
- T_{min} : the daily minimum air temperature in $^{\circ}\text{C}$
- I : the daily total solar radiation in MJ/m^2
- $3I$: the 3-day average of the daily total solar radiation in MJ/m^2
- I_{max} : the daily maximum hourly solar radiation in W/m^2
- w : the daily average wind speed in m/s

The above variables were also raised to different powers, and their multipliers were included in the stepwise regression to find the simplest formula with the highest coefficient of determination. Among the above factors, the variables that formed a

simple proposed formula with high R^2 were DT (linear), I (quadratic), and w (quadratic). The proposed formula of the daily maximum vertical temperature gradient in °C is:

$$Ver = 2.57 + 0.181DT + (0.534I - 0.00269I^2) - (1.32w - 0.208w^2) \quad (5.5)$$

The predicted formula has a high degree of correlation with a determination coefficient R^2 of 0.957 ($R=0.98$). Figure 5.2 shows the correlation between the predicted and the experimental daily maximum vertical temperature gradients for the studied period. The Figure obviously shows that the predicted values are well correlated to their corresponding experimental values.

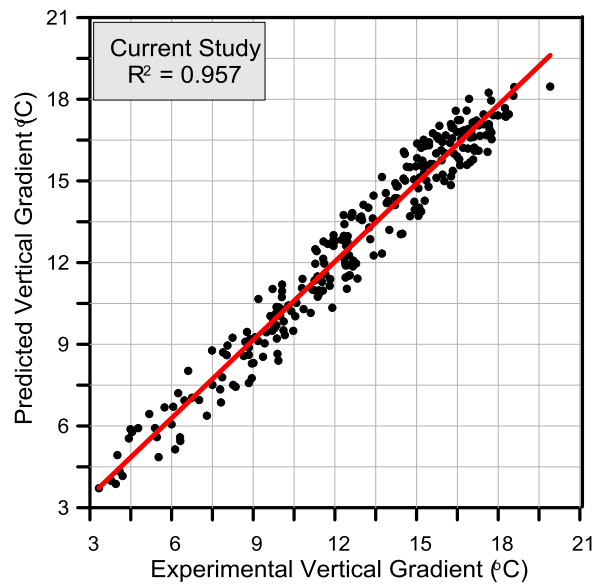


Figure 5.2 Predicted daily maximum vertical temperature gradient vs experimental daily maximum vertical temperature gradient

Using a one-dimensional finite difference sensitivity analysis, Potgieter and Gamble in 1983 [13] introduced different equations for different topping thicknesses to evaluate the maximum vertical temperature gradients. These equations were predicted based on the daily total solar radiation (I), the solar absorptivity of the concrete surface (α), the daily air temperature difference (DT), and the daily average wind speed (w). For the no black topping case, which meets the case of the experimental box-girder of the current study, their proposed equation is:

$$Ver = 28.2 \left[\frac{I \cdot \alpha}{29.089} - 0.7 \right] + 0.342(DT - 11.1) + V \quad (5.6)$$

where:

$$V = 32.3 - 4.84w + 0.771w^2 - 0.088w^3 + 0.00463w^4 \quad (5.7)$$

The Potgieter and Gamble equation was tested against the experimental values of the maximum vertical temperature gradient of the current study as shown in Figure 5.3. The figure shows that R^2 of this correlation is 0.811, which is much lower than that given by Equation 5.5.

Roberts-Wollman et al. in 2002 [14] proposed a simplified equation to predict the maximum vertical temperature gradient based on the daily maximum air temperature (T_{max}), the 3-day average of air temperature ($3T_{ave}$), and the daily total solar radiation (I). Their proposed equation is:

$$Ver = 0.9[T_{max} - 3T_{ave}] + 0.56(I - 12) \quad (5.8)$$

The Roberts-Wollman et al. equation was better correlated to the experimental values of the current study than the Potgieter and Gamble equation with R^2 of 0.935 as shown in Figure 5.4.

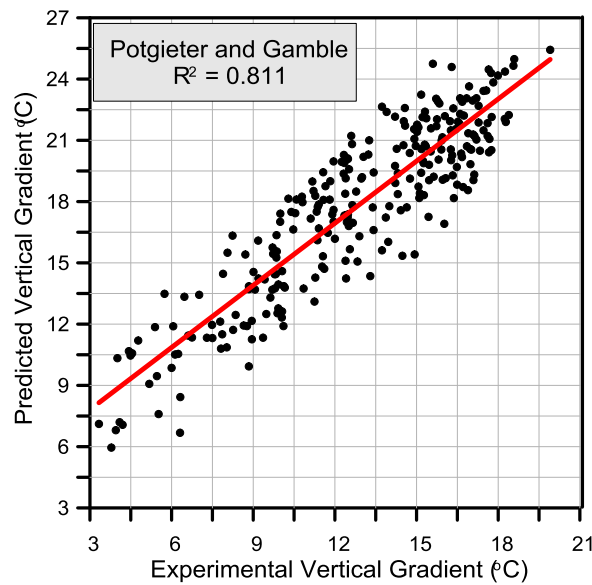


Figure 5.3 Predicted daily maximum vertical temperature gradient (Potgieter and Gamble) vs experimental daily maximum vertical temperature gradient

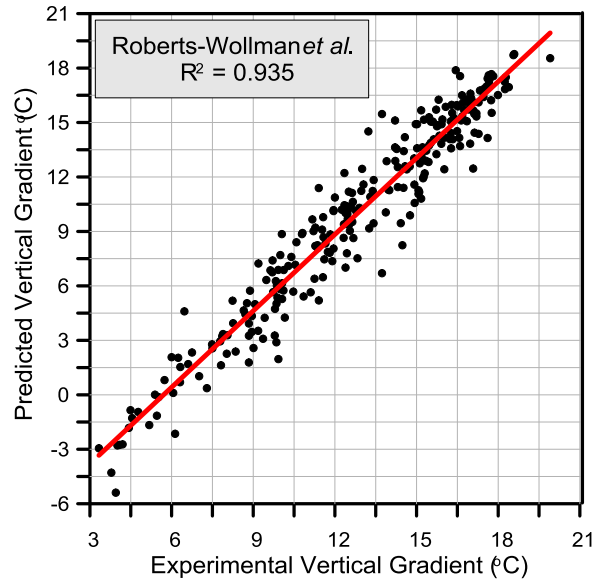


Figure 5.4 Predicted daily maximum vertical temperature gradient (Roberts-Wollman et al.) vs experimental daily maximum vertical temperature gradient

Lee and Kalkan [15] in 2012 introduced an equation to evaluate the maximum vertical temperature gradient using a two-dimensional finite element thermal analysis of a precast concrete beam. The equation was conducted based on the daily maximum (T_{max}) and daily minimum (T_{min}) air temperatures, the daily total solar radiation (I), and the daily average wind speed (w), which is given by:

$$Ver = \frac{3}{4}I + \frac{1}{15}(T_{max} - T_{min}) - V \quad (5.9)$$

where:

$$V = 0.37 + 2.93w - 0.25w^2 + 0.008w^3 \quad (5.10)$$

The R^2 of the correlation of the predicted vertical gradient values using this equation and the experimental maximum vertical gradients from the current experimental study was 0.949 as shown in Figure 5.5.

Table 5.1 shows a statistical comparison between the formula predicted in this study based on the experimental records and those predicted by Potgieter and Gamble, Roberts-Wollman et al., and Lee and Kalkan. It is clear from the table that the proposed formula in the current study gives the highest determination coefficient and the lowest errors among all of the compared equations. This reveals the high

accuracy of the proposed formula, and that it can be used with high degree of confidence to evaluate the maximum vertical temperature gradient of concrete box-girders.

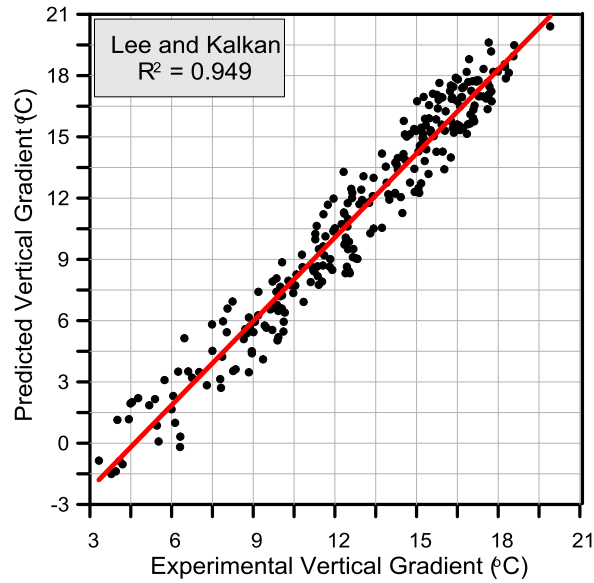


Figure 5.5 Predicted daily maximum vertical temperature gradient (Lee and Kalkan) vs experimental daily maximum vertical temperature gradient

Table 5.1 Comparison of the current predicted vertical gradient formula with other formulas from literature

Formula	R^2	AAE	MaAE	RMSE
Potgieter and Gamble	0.811	4.95	9.55	5.28
Roberts-Wollman et al.	0.935	2.93	9.13	3.54
Lee and Kalkan	0.949	1.99	6.49	2.47
Current Study	0.957	0.65	1.56	0.78

5.3 Lateral Temperature Gradients

The lateral temperature distributions across the centerline of the top slab and the bottom slab were used to calculate the temperature gradients of the top slab (TS) and the bottom slab (BS). Similar to the vertical temperature gradient, stepwise regressions were carried out as initial steps to estimate the degree of influence of each parameter and to choose simplified equations but with reasonable determination coefficient.

As for the vertical gradient, DT , I , and w were found to be effective factors, but with different weights. In addition, the inclusion of other factors was found to increase the determination coefficient. The factors that were included in the lateral gradients (TS and BS) proposed formulas were DT , I , and w , in addition to the followings:

- $3I$: the 3-day average of the total daily solar radiation
- $n/365$: the day index, which refers to the number of day from 365 days of the year

5.3.1 Top Slab Lateral Temperature Gradient

Before the presentation of the proposed equation of the lateral temperature gradient TS , the correlation of its individual variables with the recorded experimental gradients are investigated.

5.3.1.1 Correlation with Thermal Loads

The daily air temperature difference DT has similar linear correlation with TS to that with Ver , where R^2 with Ver was 0.315, while it was 0.312 with TS . On the other hand, TS has bad linear correlation with the daily total solar radiation I where R^2 equals only 0.16, while quadratic and cubic polynomials of I showed better correlations with TS . The R^2 was 0.336 for the quadratic relation, while it was 0.367 for the cubic relation. On the other hand, the linear correlation of TS with $3I$ gave R^2 equals 0.33.

The linear correlation of the daily maximum top slab lateral temperature gradient with the daily average wind speed resulted in R^2 of 0.412, while the degree of correlation increased with the increase of the degree of the relationship. The quadratic polynomial gave R^2 of 0.49, while R^2 for the cubic polynomial was 0.503.

The lateral temperature gradients occur when the solar radiation strikes one side from the bridge's superstructure with low altitude angles, while the other side is shaded. The solar angles depend mainly on the season of the year and of course on the time of the day. Therefore, the day index $n/365$ was found to be effective on the lateral gradients (TS and BS), while it is not effective on the vertical gradient (Ver).

The relationship between the daily maximum top slab lateral temperature gradient and the day index cannot be represented by linear formula, where R^2 was as low as 0.01. However, the quadratic relationship between TS and $n/365$ resulted in much higher R^2 than that of the linear relationship, which was 0.384.

5.3.1.2 Predicted Top Slab Lateral Temperature Gradient

Figure 5.6 shows the correlation between the predicted and the experimental daily maximum top slab lateral temperature gradients for the one-year period. It is clearly shown in the figure that the predicted values are well correlated to their corresponding experimental values. The predicted formula has a good degree of correlation with R^2 of 0.918 ($R=0.958$), while the AAE, the MaAE, and the RMSE were 0.7 °C, 2.83 °C, and 0.89 °C, respectively.

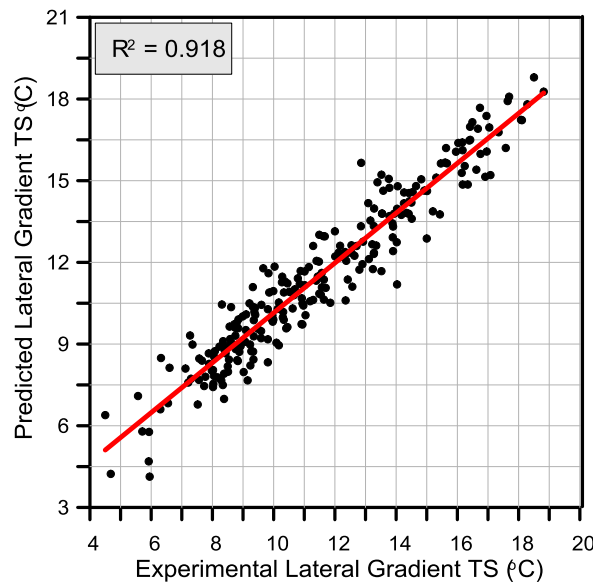


Figure 5.6 Predicted daily maximum top slab lateral temperature gradient vs experimental daily maximum top slab lateral temperature gradient

The proposed formula of the daily maximum top slab lateral temperature gradient in °C is:

$$TS = 10.21 + 0.591DT + I_s + V + N \quad (5.11)$$

Where:

$$I_s = 0.837I - 0.0218I^2 - 0.00036I^3 - 0.277(3I) \quad (5.12)$$

$$V = -13.34w + 8.86w^2 - 1.74w^3 \quad (5.13)$$

$$N = -24.2 \frac{n}{365} + 18.5 \left(\frac{n}{365} \right)^2 + 0.487 \frac{n}{365} I \quad (5.14)$$

5.3.2 Bottom Slab Lateral Temperature Gradient

The equation proposed for the daily maximum lateral temperature gradient along the centerline of the bottom slab (*BS*) is similar to that of the top slab (*TS*). The included parameters are the same and the orders of these parameters are the same. Correlations between *BS* and the effective parameters including *DT*, *I*, *w*, *3I*, and *n/365* are discussed first before the presentation of the proposed formula for *BS*.

5.3.2.1 Correlation with Thermal Loads

The linear correlation between *BS* and *DT* showed weak determination coefficient and large errors. The R^2 of this relationship is 0.22, which is obviously lower than the R^2 of the linear correlation of *DT* with *TS* and *Ver*, which were 0.312 and 0.315, respectively. The linear relationship between the daily maximum bottom slab lateral temperature gradient *BS* and the daily total solar radiation *I* resulted in a determination coefficient R^2 of 0.312. This determination coefficient is about twice that of *TS*, which was 0.16 only. The quadratic correlation increased the coefficient of determination compared to the linear correlation from 0.312 to 0.48, while the cubic relation gave better correlation with R^2 of 0.512.

In general, it can be concluded from the comparison between the correlations of the daily total solar radiation *I* with the vertical temperature gradient *Ver* and the lateral temperature gradients *TS* and *BS* that solar radiation affects the vertical temperature gradient much more than its effect on the lateral temperature gradients.

The R^2 of the linear correlation of *Ver* with *I* was 0.887, while the maximum R^2 for the linear correlation of lateral temperature gradients with *I* was 0.312 only. Similarly, The R^2 of the quadratic correlation of the vertical temperature gradient *Ver* with *I* was 0.904 as shown in Figure 5.1, while its corresponding maximum R^2 for the lateral temperature gradients was 0.48 only. On the other hand, the

coefficient of determination R^2 of the correlation of BS with $3I$ was 0.465. This value is better than that of TS , which was 0.33.

The linear correlation of BS with the daily average wind speed gave a determination coefficient R^2 of 0.406. The R^2 of the quadratic polynomial was not much better than of the linear correlation, which was 0.444. The cubic relation did not lead to any improvement from the quadratic relationship, where the coefficient of determination was also 0.444.

Similar to the daily maximum top slab lateral temperature gradient TS , the linear correlation is absolutely not suitable to represent the relationship between the daily maximum bottom slab lateral temperature gradient BS and the day index ($n/360$), while the quadratic polynomial seems to be much reasonable and accepted. The coefficient of determination R^2 of the linear relation was 0.005 only, while R^2 of the quadratic relationship was 0.492.

5.3.2.2 Predicted Bottom Slab Lateral Temperature Gradient

Figure 5.7 shows the correlation between the predicted daily maximum bottom slab lateral temperature gradient BS and the experimental daily maximum bottom slab lateral temperature gradients. The good correlation between the predicted values and their corresponding experimental values is obviously shown in Figure 5.7. The predicted formula has a coefficient of determination R^2 of 0.942 ($R=0.97$), while the AAE, the MaAE, and the RMSE were 0.68°C, 2.41°C, and 0.83°C, respectively. The proposed formula of the daily maximum bottom slab lateral temperature gradient BS in °C is:

$$BS = -1.162 + 0.393DT + I_s + V + N \quad (5.15)$$

Where:

$$I_s = 2.038I - 0.0879 + 0.00104I^3 - 0.306(3I) \quad (5.16)$$

$$V = -4.81w + 2.93w^2 - 0.46w^3 \quad (5.17)$$

$$N = -21.9 \frac{n}{365} + 16.3 \left(\frac{n}{365} \right)^2 + 0.501 \frac{n}{365} I \quad (5.18)$$

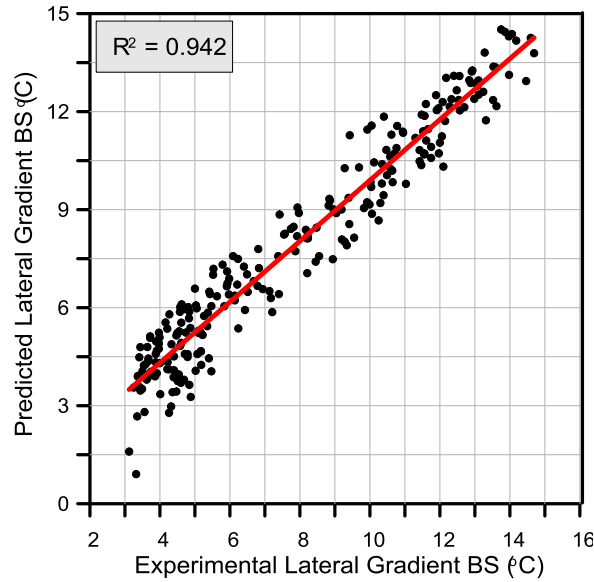


Figure 5.7 Predicted daily maximum bottom slab lateral temperature gradient vs experimental daily maximum bottom slab lateral temperature gradient

5.4 The Bridge Mean Temperature

As explained in section 4.7 in chapter 4, the mean temperature of the box-girder was estimated by calculating the sum of the products of the temperature of each thermocouple by its surrounding area at each time step and then by dividing by the total area of the box-girder as shown in Equation 4.1. The daily maximum and the daily minimum temperatures of bridges are used in design to estimate the possible longitudinal movements due the fluctuation of the climate.

After conducting a stepwise regression including many environmental factors, the daily maximum mean temperature MT_{max} was found to be very well linearly correlated to the daily maximum air temperature T_{max} . Similarly, the linear correlation between the daily minimum mean temperature MT_{min} and the daily minimum air temperature T_{min} was very good. Figures 5.8 and 5.9 show the linear correlations of MT_{max} and MT_{min} , where the coefficient of determinations R^2 were 0.967 ($R=0.983$) and 0.964 ($R=0.982$), respectively.

The proposed formulas for the maximum mean temperature MT_{max} and the minimum mean temperature MT_{min} of the box-girder are:

$$MT_{max} = 1.1T_{max} + 0.17 \quad (5.19)$$

$$MT_{min} = 1.06T_{min} + 6.54 \quad (5.20)$$

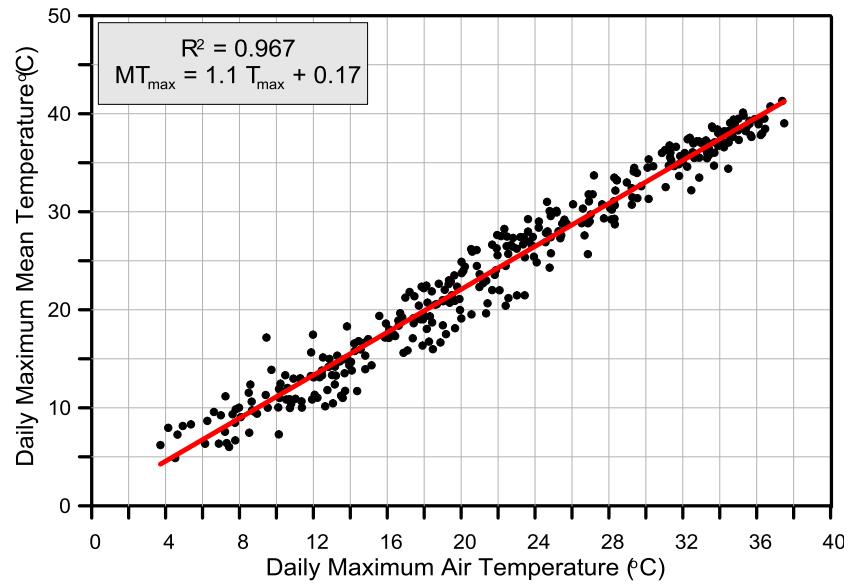


Figure 5.8 Daily maximum mean bridge temperature (MT_{max}) vs daily maximum air temperature

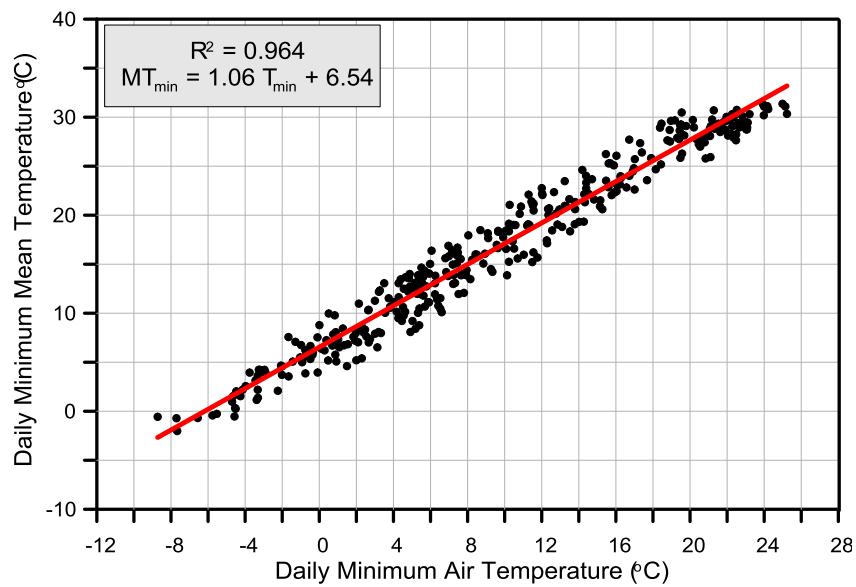


Figure 5.9 Daily minimum mean bridge temperature (MT_{min}) vs daily minimum air temperature

5.5 The In-Box Air Temperature

Similar to the mean temperature of the bridge, the temperatures of air inside the box cavity was found to have simple linear correlations with ambient air temperature. Figure 5.10 shows the high accuracy of the linear correlation between the daily maximum air temperature inside the box girder IBT_{max} and the daily maximum of ambient air temperature T_{max} , which resulted in R^2 of 0.967. Similarly, Figure 5.11 shows that R^2 equals 0.968 was resulted from the simple linear correlation of the daily minimum air temperature inside the box-girder IBT_{min} with the daily minimum of the ambient air temperature T_{min} . The R^2 of the linear correlation between the daily average of the air temperature inside the box girder IBT_{ave} and the daily average of the ambient air temperature T_{ave} is as high as 0.991 as shown in Figure 5.12.

The proposed formulas for the daily maximum IBT_{max} , the daily minimum IBT_{min} , and the daily average IBT_{ave} of the temperature of air inside the box girder are:

$$IBT_{max} = 1.07T_{max} + 0.57 \quad (5.21)$$

$$IBT_{min} = 1.06T_{min} + 5.89 \quad (5.22)$$

$$IBT_{ave} = 1.07T_{ave} + 2.73 \quad (5.23)$$

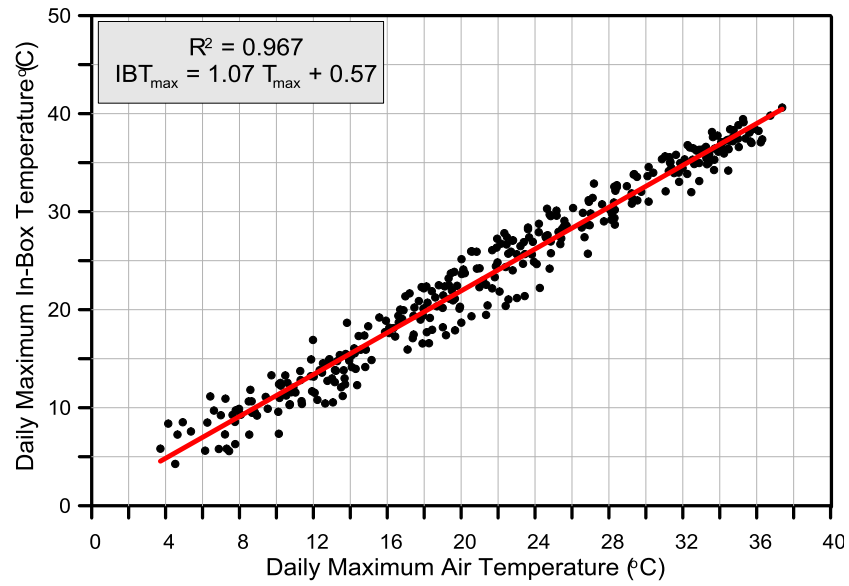


Figure 5.10 Daily maximum in-box temperature ($IBT_{\max}$) vs daily maximum air temperature

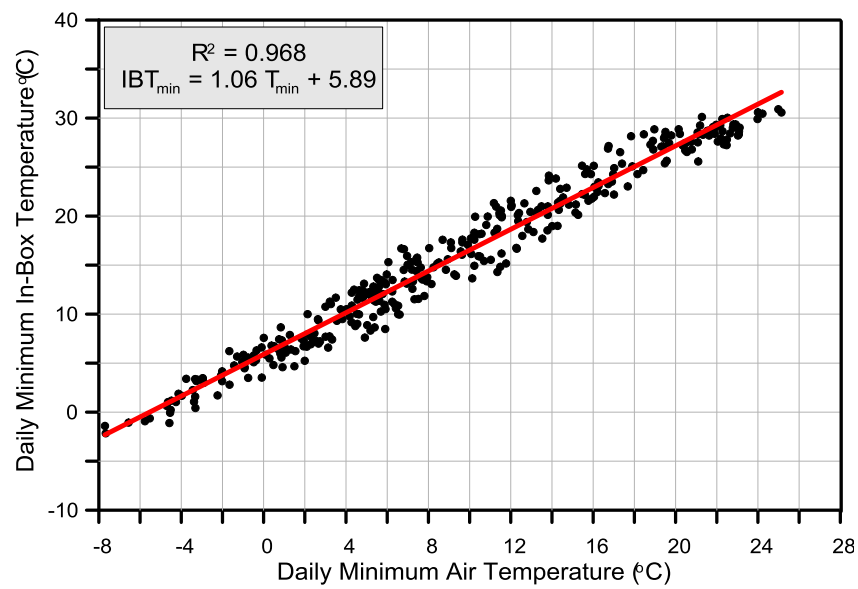


Figure 5.11 Daily minimum in-box temperature ($IBT_{\min}$) vs daily minimum air temperature

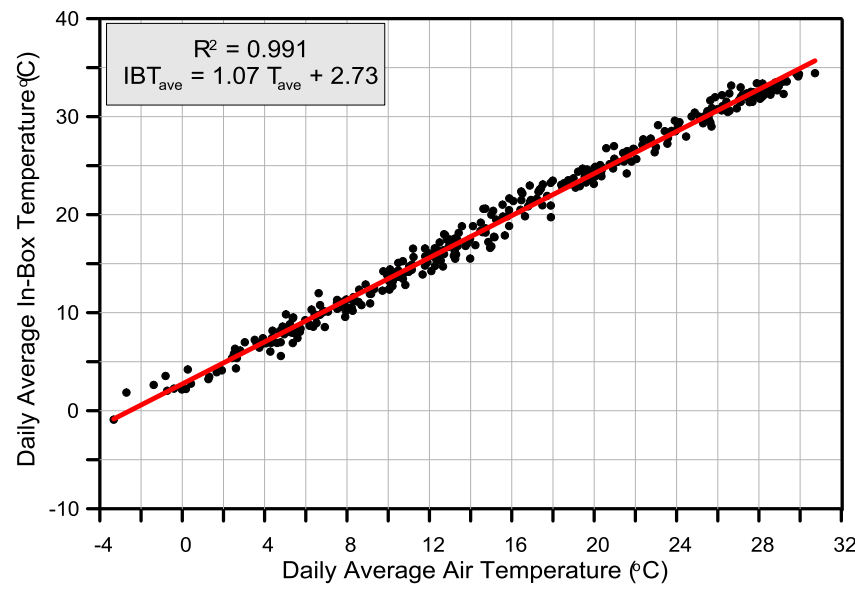


Figure 5.12 Daily average in-box temperature (IBT_{ave}) vs daily average air temperature

CHAPTER SIX

THE HEAT TRANSFER PROBLEM AND THE FINITE ELEMENT MODEL

6.1 General

The superstructures of the bridges are generally exposed to open environment conditions. Due to this type of exposure, many types of thermal loads affect the exterior surfaces of the superstructure. These loads are mainly due to the solar radiation and the heat exchange with the surrounding air. Figure 6.1 illustrates the boundary thermal loads on the exposed surfaces of the bridge superstructure.

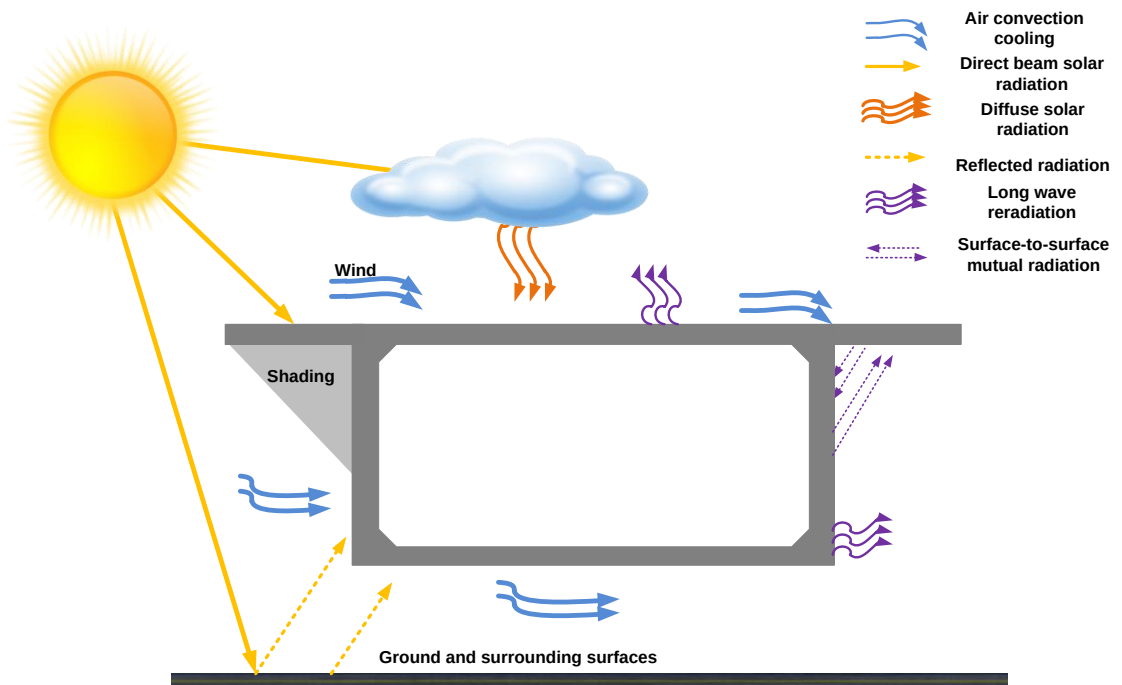


Figure 6.1 The environmental thermal loads on the box-girder

As shown in Figure 6.1, the solar radiation either attacks the exposed surface directly from the sun by the beam component or reaches the surface indirectly by the diffused component from the clouds and the weather pollutants. A part of this radiation is absorbed by the surfaces of the bridge, while the rest is reflected back to the atmosphere. The exterior surfaces of the bridge receive an amount of the reflected solar radiation from the ground and the surrounding objects depending on the tilt angle of each surface.

All grey bodies absorb some of the received thermal radiations and re-radiate a part of which again to the atmosphere by long-wave radiation, which cools the surface down depending on its radiosity and the difference of the surrounding air and the surface temperatures. Ideal grey bodies re-radiate the complete absorbed quantity of radiation, while concrete has different surface absorptivity and emissivity coefficients. A part of the re-radiated heat reaches the other surfaces of the bridge, which have mutual visions. This is called as the surface-to-surface radiation or the mutual radiation as shown in Figure 6.1.

The movement of air on the surface has also a significant role on the heating and cooling process. Depending on the surface convection properties, the speed of the wind, and the difference between the air and the surface temperatures, the convection heat transfer occurs. When the temperature of the air is lower than the surface temperature (night and early morning), the surface is cooled down by the convection cooling as illustrated in Figure 6.1.

6.2 The Analysis of Heat Transfer in Concrete Girders

6.2.1 Heat Conduction in Concrete Bridges

The process of the transfer of heat from the exterior boundaries of the concrete girder to the interior cores and vice versa is defined as heat conduction. Heat conduction is simply the process of heat transfer from one part of the material to another. The conduction process can be modeled mathematically by the Fourier partial differential equation [26], which is expressed as follows:

$$k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q = \rho C_p \frac{\partial T}{\partial t} \quad (6.1)$$

Where:

k is the coefficient of the thermal conductivity of concrete measured in $W/m^\circ C$. Considering an isotropic material, k is equal along all directions x , y , and z . The thermal conductivity of concrete depends mainly on its composition and moisture condition.

C_p is the specific heat of concrete measured in $J/kg^\circ C$. The specific heat can be defined as the amount of heat required to increase the temperature of a unit mass by one degree.

ρ is the density of concrete measured in kg/m^3 . T is the concrete temperature at any point have the coordinates x, y and z in the concrete mass at any time, t . Q is the amount of heat per each unit volume generated inside the concrete by cement hydration (W/m^3). Q is considered only during the early age of concrete, while it can be taken as zero during the rest life span of concrete.

6.2.2 The Boundary Conditions

The thermal loads applied on the boundaries of the concrete girder can be represented by,

$$k \frac{\partial T}{\partial x} n_x + k \frac{\partial T}{\partial y} n_y + k \frac{\partial T}{\partial z} n_z + q = 0 \quad (6.2)$$

Where n_x , n_y , and n_z are the direction cosines of an outwards vector normal to the boundary [26].

The term q is the total heat flux affecting the exposed boundaries measured in W/m^2 , which is the sum of the following heat fluxes:

$$q = q_c + q_s + q_g + q_m + q_r \quad (6.3)$$

6.2.2.1 Convection (q_c)

q_c is the term used to represent the heat convection affecting on all of the superstructure surfaces, which occurs between the superstructure surfaces and the surrounding air because of the temperature difference between them.

$$q_c = h_c (T_s - T_a) \quad (6.4)$$

Where:

T_s is the surface temperature of the superstructure, while T_a is the temperature of the air affecting on the surface. h_c is the convection coefficient of heat transfer measured in W/m^2K , which depends mainly on the speed of the wind and on the location and tilt angle of the surface. Thus, exterior surfaces have different coefficients from interior surfaces (inside the box-girder) and top surface has different coefficient from vertical or bottom surfaces.

On exterior surfaces, the heat convection is a mixed of the free and the forced heat convections. On the other hand, on the interior surfaces of the box-girder (inside the cavity), only free convection takes place. Inside the box-girder, the speed of air is zero, hence, the forced convection component is set to zero.

Empirical formulas to estimate the heat transfer coefficients h_c for concrete box-girder bridges were recommended by Kehlbeck [72], which were used in this study,

$$h_c = 3.83\vartheta + 4.67 \quad (6.5)$$

$$h_c = 3.83\vartheta + 2.17 \quad (6.6)$$

$$h_c = 3.83\vartheta + 3.67 \quad (6.7)$$

$$h_c = 3.5 \quad (6.8)$$

Equations 6.5 and 6.7 were used to calculate the convection coefficients for the top surface of the top slab and the exterior surfaces of the webs, while Equation 6.6 was used for the lower surfaces of the bottom slab and of the cantilevers of the top slab. On the other hand, Equation 6.8 was used to estimate the convection coefficient for the interior surfaces of the box-girder.

6.2.2.2 Solar Radiation (q_s)

q_s refers to the thermal solar radiation that reaches the exterior boundaries of the box-girder, which is represented by,

$$q_s = aI_s \quad (6.9)$$

Where:

a is the absorption coefficient (absorptivity) of the bridge surfaces, while I_s is the total radiation received from the sun by a horizontal surface on the ground.

$$I_s = I_{bh} + I_{dh} \quad (6.10)$$

Where I_{bh} is the direct beam component of solar radiation on a horizontal surface, which refers to the direct effect of sunrays. On the other hand, I_{dh} is the diffused component of solar radiation, which refers to the solar radiation reaches the horizontal surfaces on the earth after having been scattered by the atmosphere's clouds and pollutant particles.

In the current research and as discussed in chapter 3, the used solar radiation sensor measures the total solar radiation (I_s) reaching the top surface of the box-girder directly. The beam I_{bn} and diffuse I_{dn} solar radiation components reaching vertical or inclined surfaces can be estimated using the following expressions:

$$I_{bn} = I_{bh} \frac{\cos\theta}{\cos\theta_1} \quad (6.11)$$

$$I_{dn} = I_{dh} \frac{1+\cos\delta}{2} \quad (6.12)$$

Where:

θ is the solar incidence angle, which is the angle between the sunrays and the normal of the surface. θ_1 is the solar zenith angle, which is a derived solar angle measures the angle between the directly overhead and the geometric center of the disk of the sun. δ is the inclination angle of the surface with the horizontal plane. Detailed definitions of the basic and the derived solar angles are given in Appendix A. It should be noted that shaded areas receive no direct beam radiation, while they receive diffused radiation.

6.2.2.3 Reflected Radiation (q_g)

q_g is the component of solar radiation reflected from the ground and the surrounding objects. The fraction of the reflected radiation by a surface to the total radiation incidence on it is defined as albedo.

$$q_g = aI_g \quad (6.13)$$

where I_g is the reflected solar radiation from the ground and the surrounding objects,

$$I_g = \beta_g I_s \left(\frac{1 - \cos \delta}{2} \right) \quad (6.14)$$

Where, β_g is the reflectivity of the ground and surrounding objects (albedo). The reflected radiation affects on all of the surfaces that have mutual vision with the ground or the surrounding objects, hence, the ground reflection has no effect on the top surface of the box-girder. The reflected radiation strikes surfaces regardless of shading effect.

6.2.2.4 Mutual Radiation (q_m)

q_m is the mutual irradiation between the surfaces of the box-girder, which is gained from the mutual vision surfaces due to the surface-to-surface radiation between them.

6.2.2.5 Long-Wave Radiation (q_r)

The long-wave radiation component q_r describes the net of the radiation heat transfer between the exposed surfaces and the surrounding air. Thus, the combined effect of the surface radiosity and the irradiation of the ambient air, and is given by:

$$q_r = \epsilon \beta_s (T_s^4 - T_a^4) \quad (6.15)$$

Where ϵ is the emissivity of the concrete surfaces, and β_s is the Stefan-Boltzmann constant, which has a value of $5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$.

This term calculates the amount of the heat emitted from the bridge surfaces to the surrounding atmosphere by log-wave radiation, which contributes the night cooling of the exposed surface. The Fourier's heat transfer equation (Equation 6.1) is a linear partial differential equation, and so as the first four boundary thermal loads that are described in Equation 6.3. However, q_r is a fourth degree nonlinear equation, thus it renders the heat transfer process in the bridge box-girder into a nonlinear problem [68].

6.3 The Thermal FE Model of the Box-Girder

The COMSOL 4.3a multiphysics Finite Element (FE) package [23] was used in this study to perform the transient thermal analysis of the box-girder bridge segment and the following studies. The heat transfer module of COMSOL and its heat transfer with surface-to-surface radiation interface were used to solve the Fourier's heat transfer partial differential equation and to simulate the boundary thermal conditions described in Equation 6.2, simultaneously.

6.3.1 Element Type and Order

In COMSOL, it is required to define the type and order of the elements used in the meshing process. In general, in the current study, tetrahedral elements were used to mesh the volume of the concrete box-girder for heat conduction, while triangular elements were used to mesh the boundary surfaces. To optimize the analysis quality and the time required for solution, quadratic elements were chosen for temperature calculation, while linear elements were used for surface radiosity. Trials showed that the use of quadratic elements for surface radiosity leads to a slightly better agreement with experimental results, but increases the solution time significantly.

6.3.2 Mesh Size

Extremely fine mesh was used in the heat transfer analysis of the box-girder. Figure 6.2 shows the meshed box-girder. As shown in Figure 6.2, the mesh density was increased around the thermocouple locations to increase the accuracy of the predicted temperatures there. The 6.89 m^3 volume of the box-girder segment was meshed using more than 76,000 elements, in addition to about 18,000 fictitious

triangular surface elements. Figure 6.3 shows the mesh quality. The average quality of the mesh was more than 0.7, which reflects the high mesh quality and the capability of predicting the concrete temperatures with high accuracy, especially around the thermocouples where element quality exceeds 0.9.

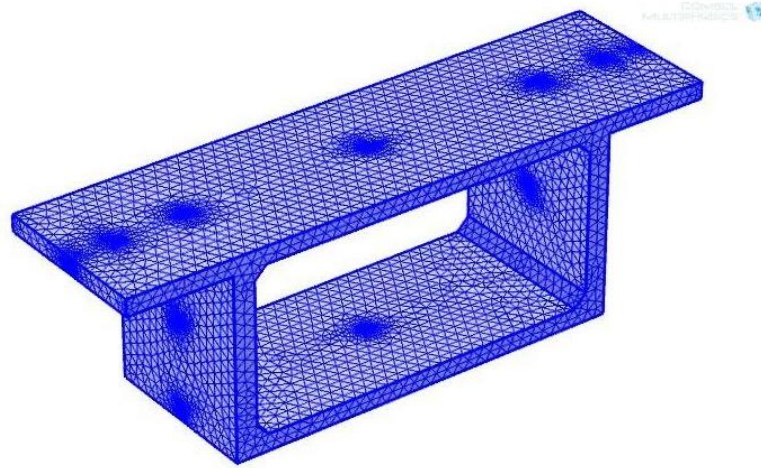


Figure 6.2 The mesh of the box-girder segment

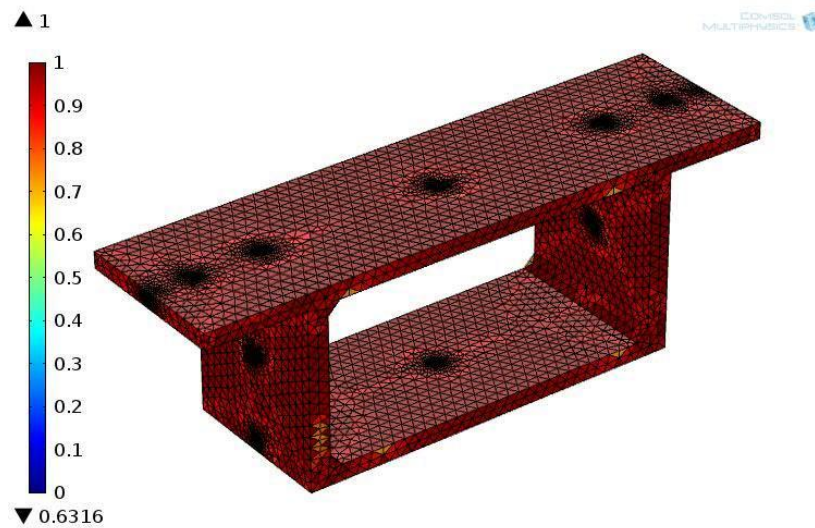


Figure 6.3 The quality of the mesh's elements

6.3.3 Radiosity and Mutual Radiation

Two methods are offered by COMSOL to estimate the view factors and solve the irradiation and the radiosity of the box-girder surfaces. The first method is the hemi-cube method, while the second is the direct integration method. Direct integration is a more simplified and a faster method, however with lower accuracy than the hemi-cube method. Where the retardation of the elements faces by the other elements is not taken into consideration, hence, this method ignores the shadowing effect [23]. On the other hand, the hemi-cube method considers the shadowing effect, and therefore it has higher accuracy than the direct integration method, however, it is more complicated and increase the solution time considerably.

The hemi-cube method estimates the view factor of the face of each element in the mesh by taking digital images of the studied geometry in five directions. The required time for solving the surface irradiation and radiosity changes quadratically with the virtual snapshots' resolution [23]. Because shadowing effect must be taken into consideration, in the current heat transfer analysis, the hemi-cube method was used with an irradiation resolution of 256 pixels.

6.3.4 Material Thermal Properties

The material properties set used in the heat transfer analysis in the current study was selected carefully so that it can efficiently model the heat transfer process in the experimental box-girder segment, assuming a homogeneous, isotropic, and independent of time material. The used concrete properties were as follows:

- 1- Thermal conductivity $k = 1.5 \text{ W/(mK)}$,
- 2- Specific heat $c = 950 \text{ J/(kgK)}$,
- 3- Concrete density $\rho = 2400 \text{ kg/m}^3$.

On the other hand, the surface emissivity and surface absorptivity were taken as 0.85 and 0.5, respectively.

6.3.5 Initial Temperature

Many previous researchers [5, 15, 49, 65] showed that the using of air temperature at 12:00 AM as the uniform initial bridge temperature can lead to good agreement with experimental results. Other scholars [52, 73] used the air temperatures at 6:00 AM to 8:00 AM as initial temperatures. In this work, the thermal analysis of the box-girder was initiated at 12:00 AM, 72 hours before the target day and the recorded air temperature at the starting time was considered as the uniform initial temperature of the box-girder.

A time step of one hour was verified by many previous researchers [49, 64, 72]. In the current experimental work and as explained in chapter 3, the measurements of thermocouples and environmental sensors were recorded at time steps of 30 minutes. Therefore, a time step of 30 minutes was used in the thermal analysis of this chapter for verification purposes.

6.4 Verification of the Finite Element Model

Three sunny days were selected to compare the predicated temperatures from the finite element thermal analysis with the recorded temperatures from the experimental box-girder segment. The temperature results of the day with the recorded maximum vertical temperature gradient are presented in this chapter, which is the 14-June-2014. The maximum lateral temperature gradient was recorded in 22-December-2013. This day is also selected for comparison and verification purposes. Another sunny hot day was chosen from the summer of 2013, which is 10-July.

Two types of temperature distributions were used to compare the predicted temperatures with the recorded temperatures. The first is the temperature variation at each thermocouple during the 24 hours of the tested day, while the second is the vertical temperature distribution along the depth of the box-girder (along the centerlines of SW and NW) recorded at specific time steps.

6.4.1 Daily Temperature Variation of Thermocouples

The temperature variations during the selected three sunny days for specific thermocouples are shown in Figures 6.4 through 6.27. Four representative thermocouples from each of the SW, the NW, the TS, and the BS were selected to visualize the comparison of the predicted temperatures with the recorded temperatures. These thermocouples are SW1 and SW6 that are located along the south web at the top surface and at the level of the bottom surface of the top slab, while SW10 and SW16 are located at the centroid of the south web and at the central depth of the bottom slab along the south web. Similarly, NW1, NW6, NW10, and NW16 are located at the same locations, respectively, but along the north web. In addition, four thermocouples are distributed along the centerline of the top slab. TS1 and TS17 are the southern and the northern edge thermocouples. TS9 is the centroid thermocouple, while TS6 is located 1.5 *m* from TS9. Similarly, BS1 and BS9 are the southern and northern edge thermocouples along the centerline of the bottom slab, while BS5 is the centroid thermocouple and BS2 is located 1.5 *m* from the BS5. Figures 3.15 and 3.16 show the locations of all thermocouples.

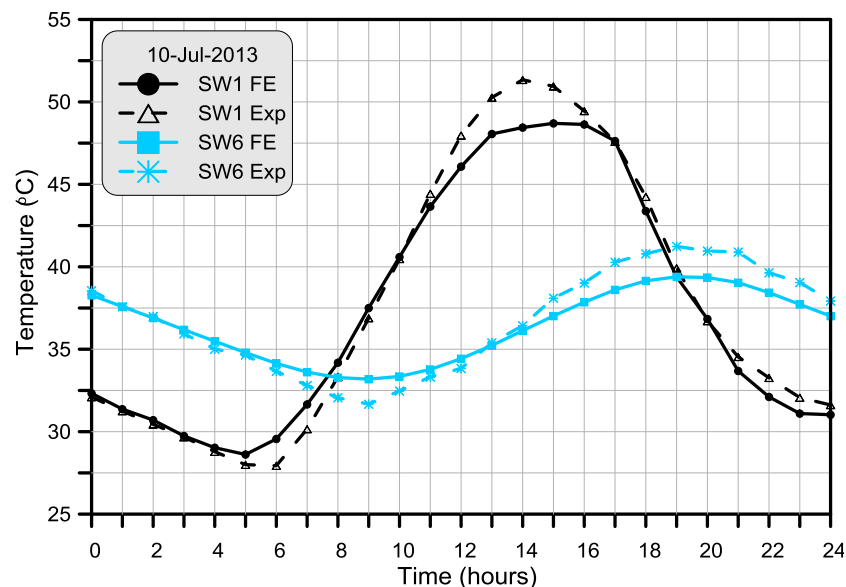


Figure 6.4 Hourly experimentally recorded and FE predicted temperatures at thermocouples SW1 and SW6 in 10-July-2013

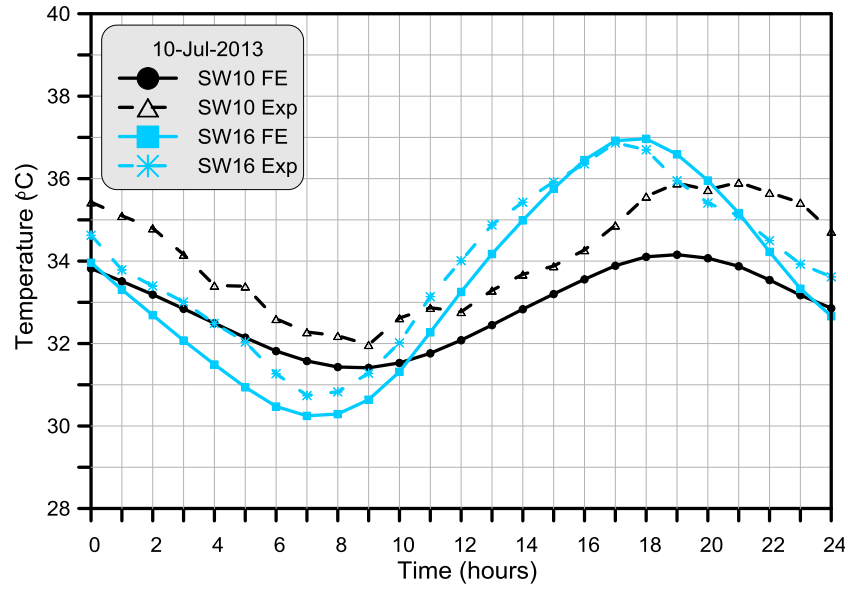


Figure 6.5 Hourly experimentally recorded and FE predicted temperatures at thermocouples SW10 and SW16 in 10-July-2013

The degree of agreement between the predicted and the recorded temperatures is measured using the Average Absolute Error (AAE), which can be estimated by equation 5.2.

Where T_{FE} is the finite element predicted temperature, T_{Exp} is the experimental record of temperature for the same point at the same time step, and n is the number of records. In the case of the daily temperature variation at each thermocouple, n equals the number of time steps, which is 48 for the day.

The Maximum Absolute Error (MaAE) and the Minimum Absolute Error (MiAE) are also used as statistical verification tools. The MaAE and the MiAE are the maximum and the minimum calculated absolute differences between the predicted and the recorded temperatures along the n measurements.

As illustrated in Figure 6.4, good agreement is shown between the predicted and the recorded temperatures of SW1 and SW6 in 10-July, while gaps between the predicted and the recorded temperatures increase around the times of the daily maximum and minimum temperatures. This trend was noticed for most of the visualized thermocouples. The AAE for SW1 was 0.93°C, while it was 0.88°C for SW6, which reflects a well agreement between the predicted and the recorded

temperatures. On the other hand, the MiAE for SW1 and SW6 were 0.04°C and 0.01°C , while their MaAE were 2.89°C and 1.86°C , which again reveals that the predicted temperatures agree well with the experimental ones. Another notice is that the behavior of variation with time was almost the same for both as shown in Figure 6.4.

Similar results were recorded for SW10 and SW16. For SW10, AAE is 1.25°C , while MiAE and MaAE were 0.55°C and 2.24°C . Thus, in average, SW10 exhibited higher deviation than SW1 as shown in Figure 6.5, but its maximum deviation (error) was lower. SW16 showed in general better agreement than SW10 did, as illustrated in Figure 6.5. The AAE, MiAE, and MaAE for SW16 were 0.58°C , 0.05°C , and 1.1°C , respectively.

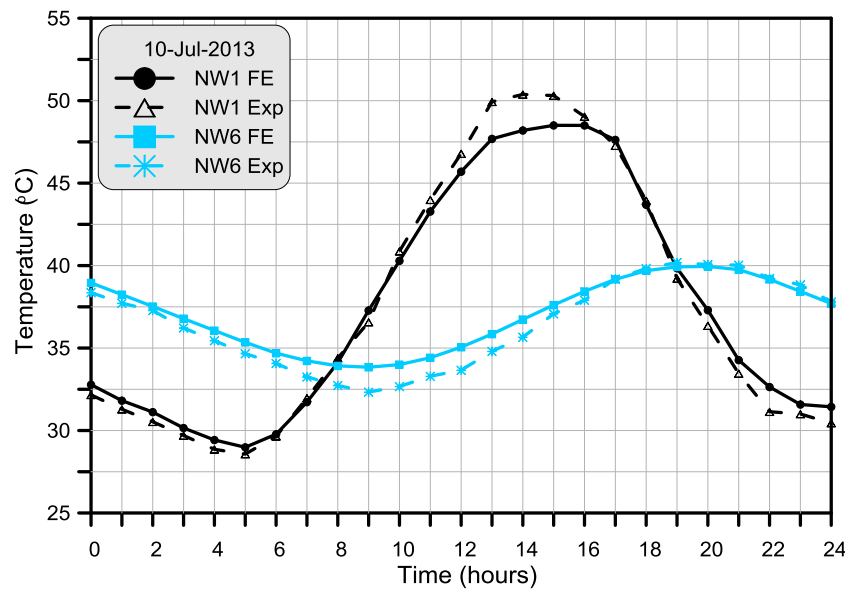


Figure 6.6 Hourly experimentally recorded and FE predicted temperatures at thermocouples NW1 and NW6 in 10-July-2013

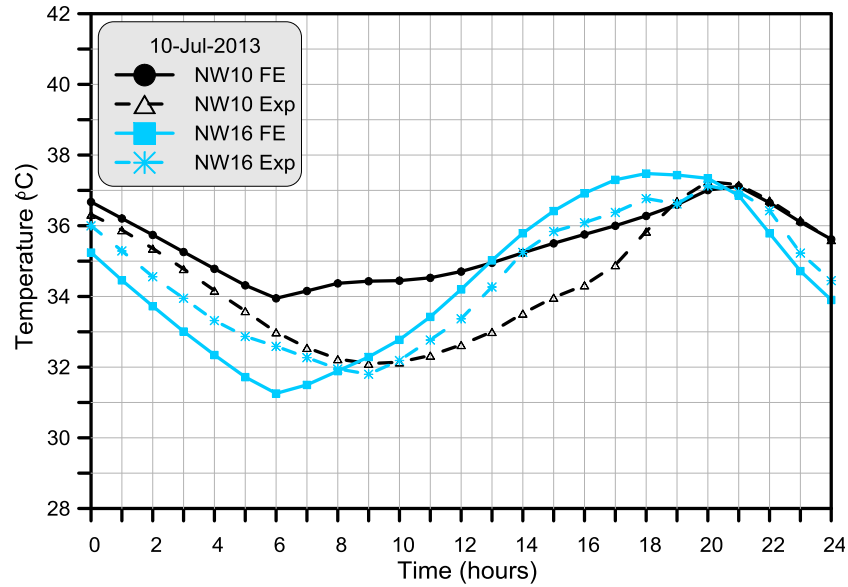


Figure 6.7 Hourly experimentally recorded and FE predicted temperatures at thermocouples NW10 and NW16 in 10-July-2013

The thermocouples of the north web followed similar trend of variation to that of the south web as shown in Figures 6.6 and 6.7. NW1 and NW6 showed better agreement between the predicted and the recorded temperatures than NW10 did. Moreover, NW16 showed the lowest AAE and MaAE values among the four thermocouples. The AAE values for SW1, SW6, SW10, and SW16 were 0.93°C, 0.88°C, 1.25°C, and 0.58°C, respectively, while the MaAE values were 2.89°C, 1.86°C, 2.24°C, and 1.1°C, respectively.

Figures 6.8 and 6.9 show that the predicted temperatures of TS thermocouples follow a fashion of variation with time similar to that of the recorded temperatures from the experimental box-girder. However, the variation was little higher than that of the SW and NW. The AAE values in 10-July of TS1, TS6, TS9, and TS17 were 1.24°C, 1.07°C, 1.12°C, and 1.23°C, respectively, while the MaAE values for the same sequence were 2.81°C, 2.46°C, 2.57°C, and 2.76°C, respectively.

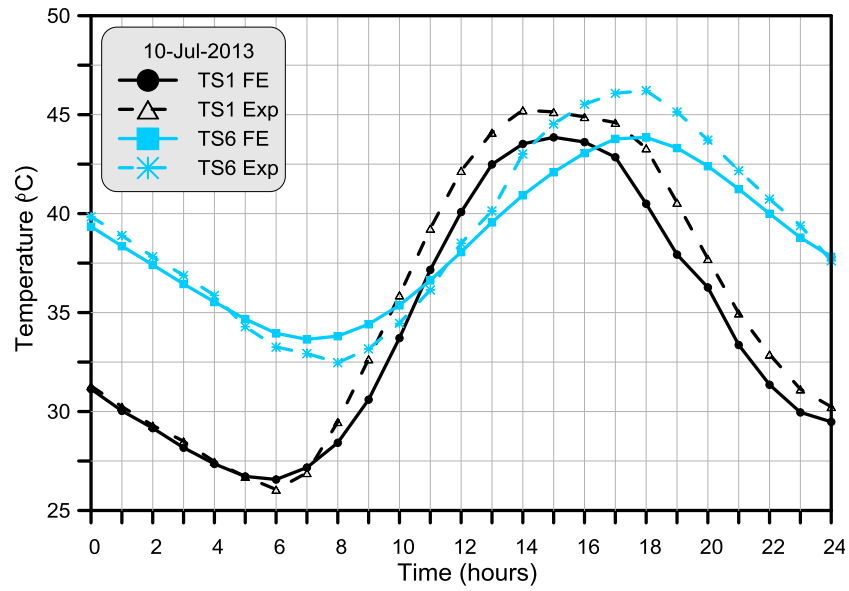


Figure 6.8 Hourly experimentally recorded and FE predicted temperatures at thermocouples TS1 and TS6 in 10-July-2013

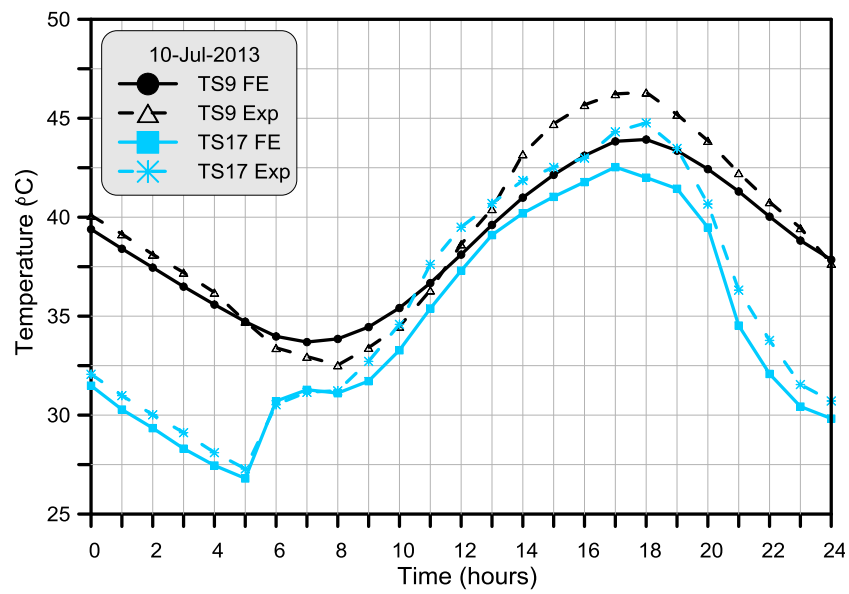


Figure 6.9 Hourly experimentally recorded and FE predicted temperatures at thermocouples TS9 and TS17 in 10-July-2013

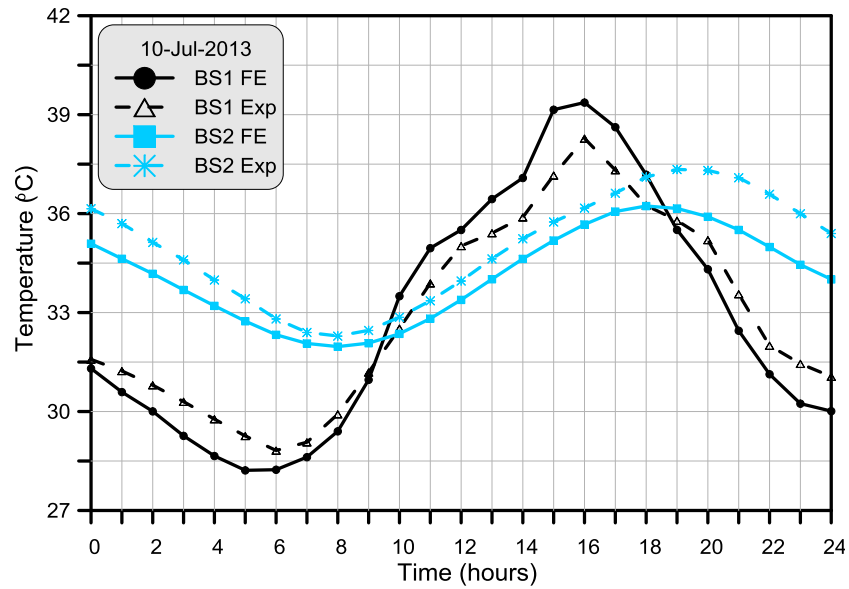


Figure 6.10 Hourly experimentally recorded and FE predicted temperatures at thermocouples BS1 and BS2 in 10-July-2013

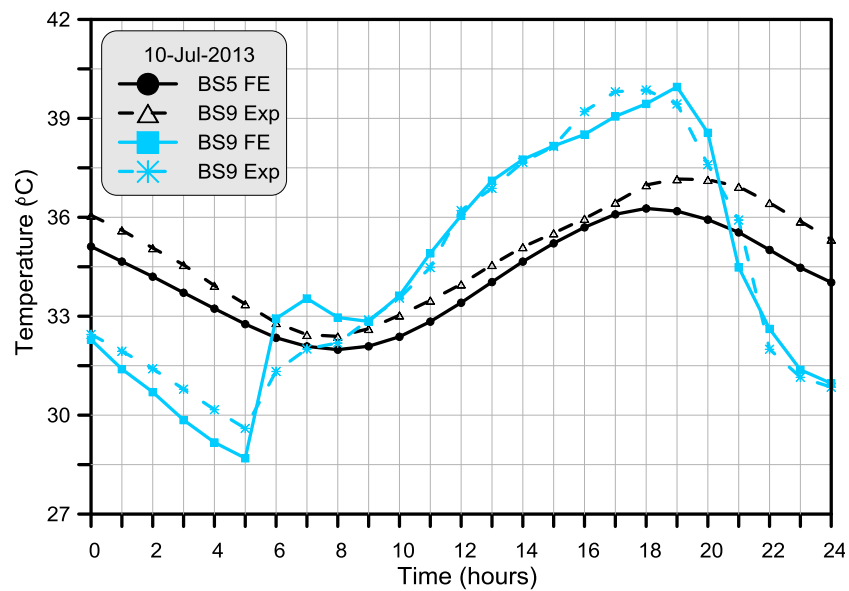


Figure 6.11 Hourly experimentally recorded and FE predicted temperatures at thermocouples BS5 and BS9 in 10-July-2013

Figures 6.10 and 6.11 show the comparison results of the BS thermocouples. The figures show that in average, BS show better agreement between the predicted and the recorded temperatures than SW, NW, and in general than TS. For the four

thermocouples of the bottom slab, the AAE was less than 1°C and the MaAE was less than 2°C.

Figures 6.12 to 6.19 show the comparison temperatures for the same couples of thermocouples in 22-December-2013. The results in general show good agreement between the predicted and the recorded temperatures. The AAE for the 16 selected thermocouples ranged from 0.24°C to 1.27°C, while the MaAE was in the range of 0.88°C to 2.56°C.

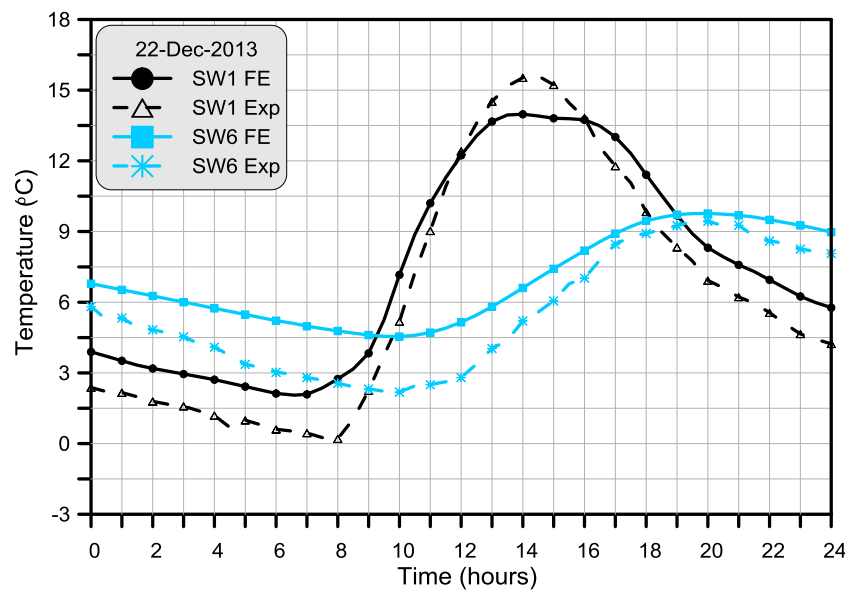


Figure 6.12 Hourly experimentally recorded and FE predicted temperatures at thermocouples SW1 and SW6 in 22-December-2013

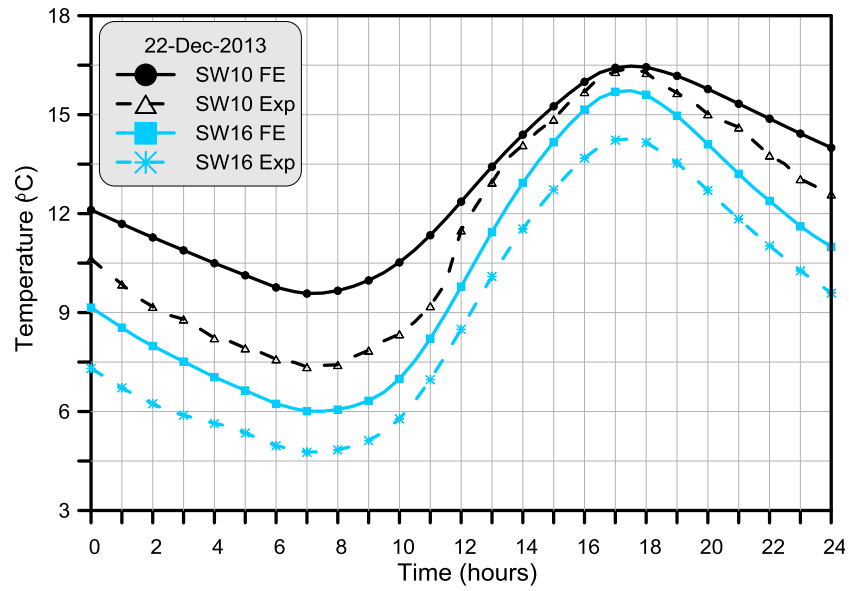


Figure 6.13 Hourly experimentally recorded and FE predicted temperatures at thermocouples SW10 and SW16 in 22-December-2013

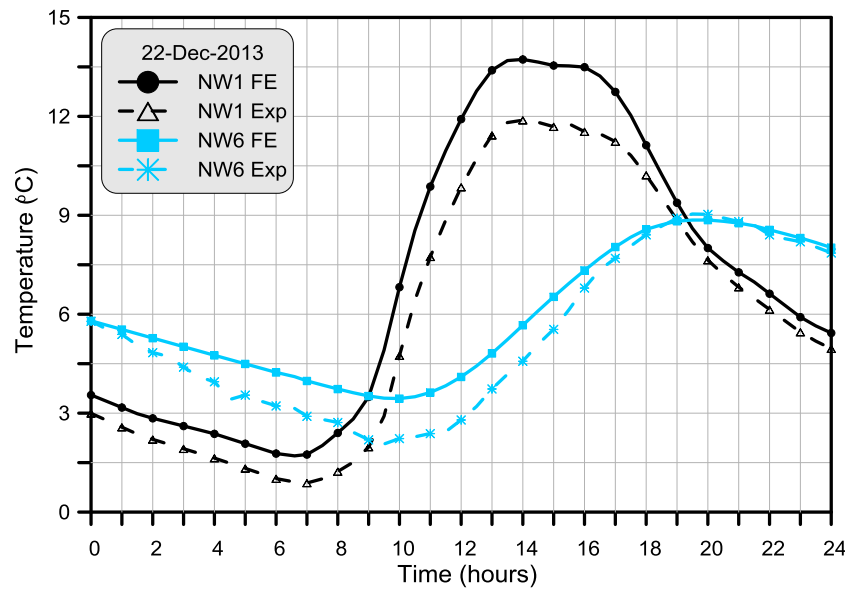


Figure 6.14 Hourly experimentally recorded and FE predicted temperatures at thermocouples NW1 and NW6 in 22-December-2013

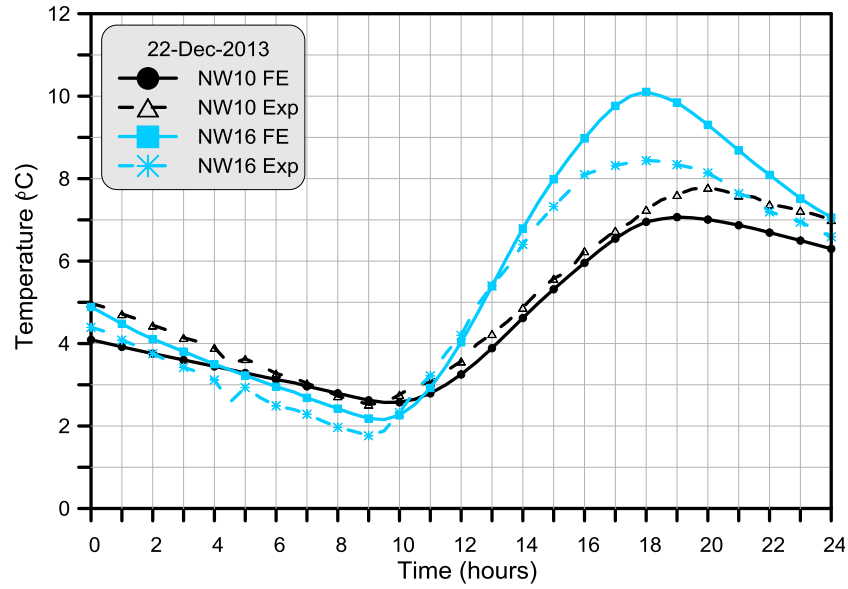


Figure 6.15 Hourly experimentally recorded and FE predicted temperatures at thermocouples SW10 and SW16 in 22-December-2013

As shown in Figure 6.12, the experimental records of SW1 were less than the predicted temperatures, but during the peak temperature period, which extended from 12:00 PM to 4:00 PM, the recorded temperatures were higher than the predicted temperatures. On the other hand, for the rest of SW thermocouples and for NW1, the predicted temperatures were higher than the recorded temperatures as shown in Figures 6.12 through 6.14. Thermocouples NW6, NW10, and NW16 show that the variation behavior with time is the same for the predicted and recorded temperatures, however, the predicted temperatures were higher in some intervals and lower in others than the recorded temperatures.

During the 24 hours of 22-December, SW thermocouples showed the highest AAE values, while BS thermocouples showed the lowest values among the four groups. The ranges of AAE for the selected thermocouples of the four groups SW, NW, TS, and BS were 1.35°C to 1.43°C, 0.41°C to 1.11°C, 1°C to 1.27°C, and 0.24°C to 1.06°C, respectively. While the MaAE values for the four groups were in the sequence of 1.83°C to 2.53°C, 0.88°C to 2.13°C, 2.27°C to 2.56°C, and 0.54°C to 2.1°C, respectively. Figures 6.16 and 6.17 for TS1, TS6, TS9, and TS17 show good agreement between the predicted and the recorded temperatures. However, Figures

6.18 and 6.19 show that the agreement of BS thermocouples is better than that of TS thermocouples.

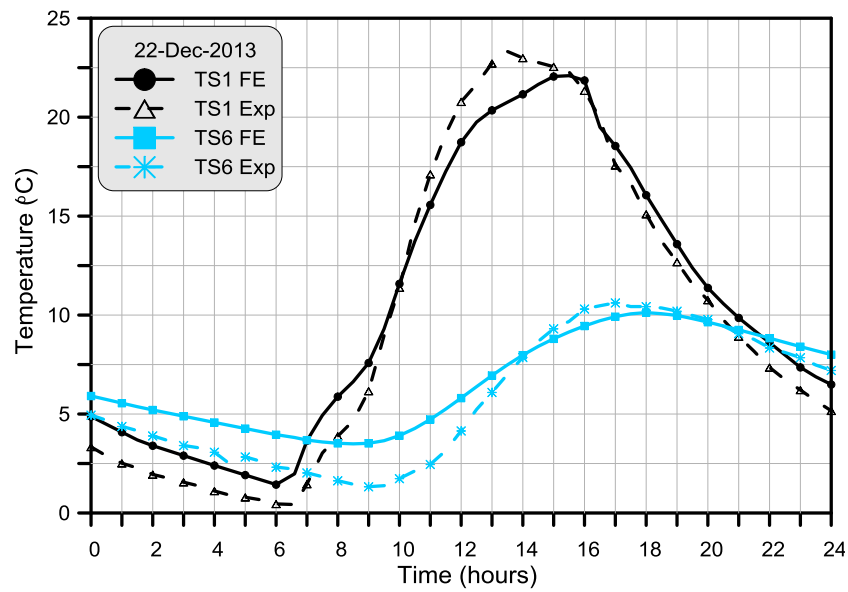


Figure 6.16 Hourly experimentally recorded and FE predicted temperatures at thermocouples TS1 and TS6 in 22-December-2013

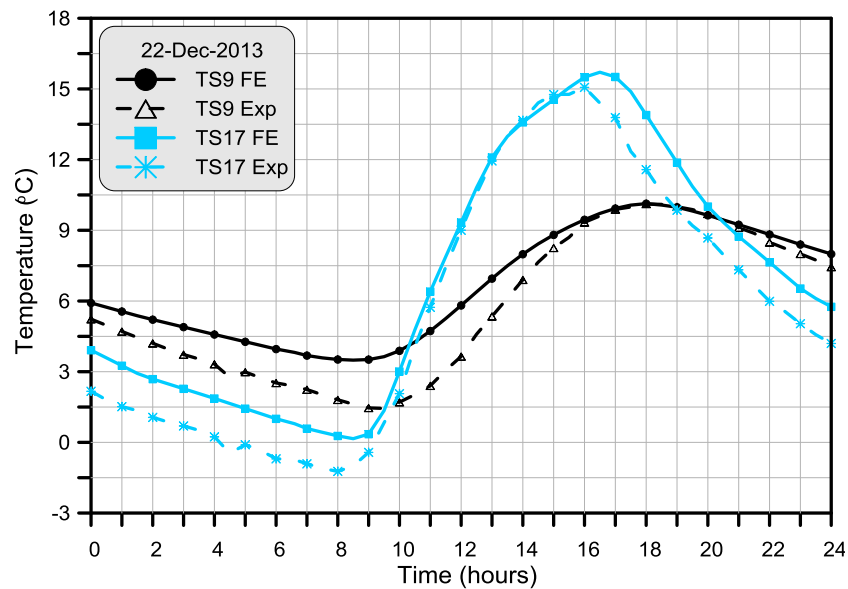


Figure 6.17 Hourly experimentally recorded and FE predicted temperatures at thermocouples TS9 and TS17 in 22-December-2013

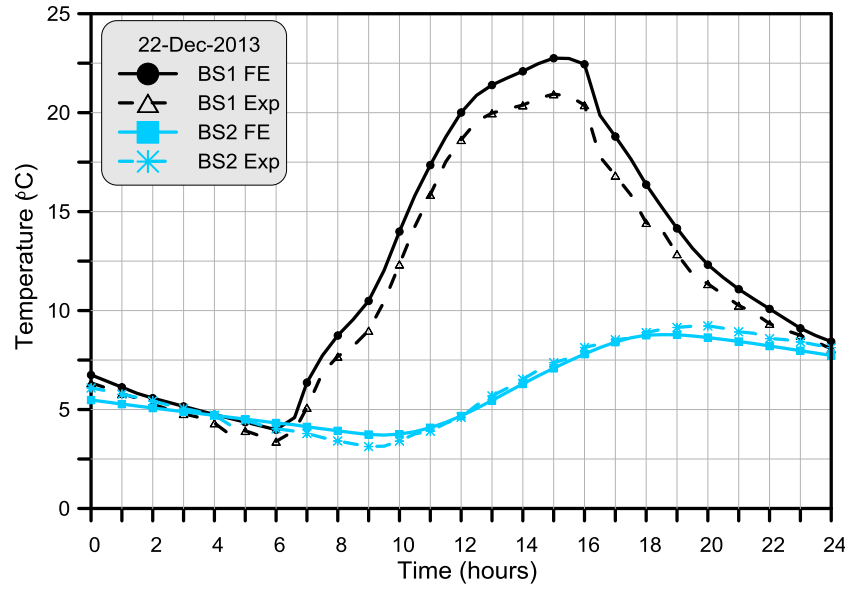


Figure 6.18 Hourly experimentally recorded and FE predicted temperatures at thermocouples BS1 and BS2 in 22-December-2013

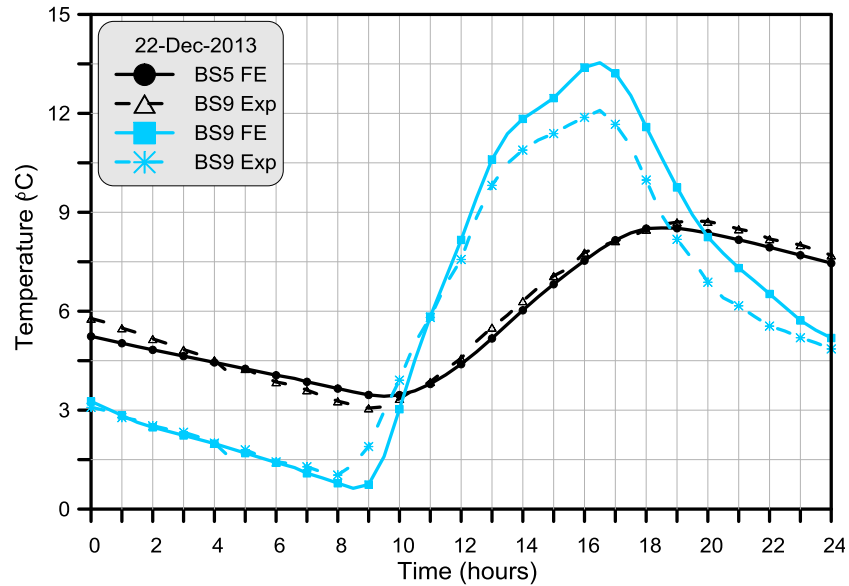


Figure 6.19 Hourly experimentally recorded and FE predicted temperatures at thermocouples BS5 and BS9 in 22-December-2013

Figures 6.20 through 6.27 show the comparison results of the selected 16 thermocouples in 14-June-2014. It is recorded that both AAE values and MaAE values were mostly higher in 14-June than in 10-July and 22-December. However, the variation still in the accepted range where the maximum recorded AAE for the

presented thermocouples was less than 2°C, while the maximum MaAE for the 16 thermocouples was less than 3.1°C.

The AAE for SW1, SW6, SW10, and SW16 was in the range of 0.82°C to 1.34°C, while it was in the range of 0.73°C to 1.46°C for NW1, NW6, NW10, and NW16. For TS1, TS6, TS9, and TS17, AAE ranged from 1.57°C to 1.91°C, while it ranged from 0.77°C to 1.28°C for BS1, BS2, BS5, and BS9. Furthermore, the MaAE values for the same sequence of the SW, NW, TS, and BS groups were in the ranges of 1.87°C to 2.79°C, 1.13°C to 2.5°C, 2.44°C to 3.07°C, and 1.66°C to 2.88°C, respectively. Thus, it can be noticed that the better agreements between the predicted and the recorded temperatures were shown for the NW and BS groups, while the highest variations were recorded for the TS group.

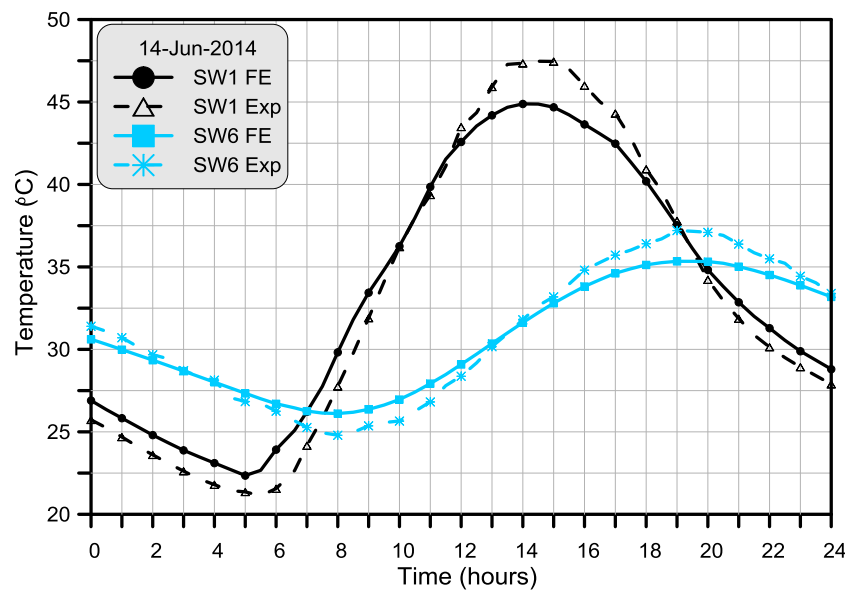


Figure 6.20 Hourly experimentally recorded and FE predicted temperatures at thermocouples SW1 and SW6 in 14-June-2014

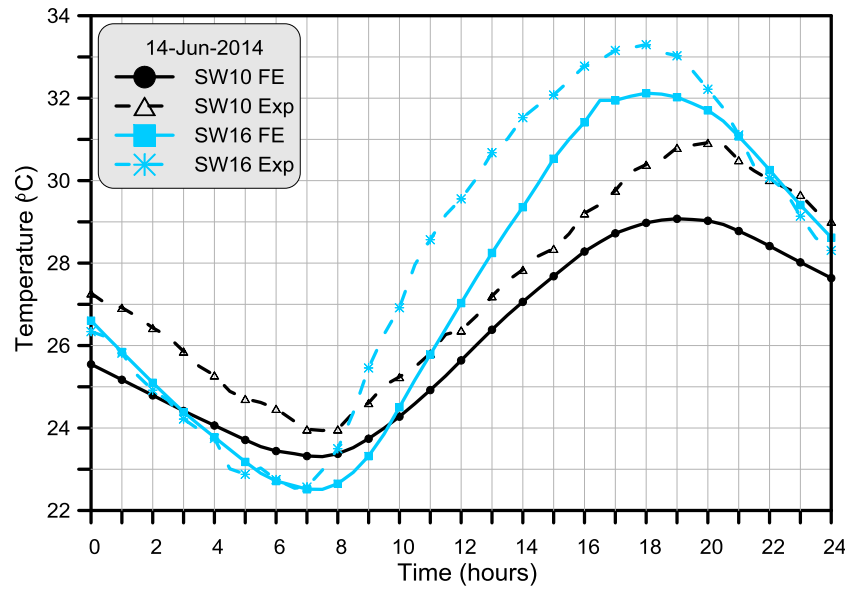


Figure 6.21 Hourly experimentally recorded and FE predicted temperatures at thermocouples SW10 and SW16 in 14-June-2014

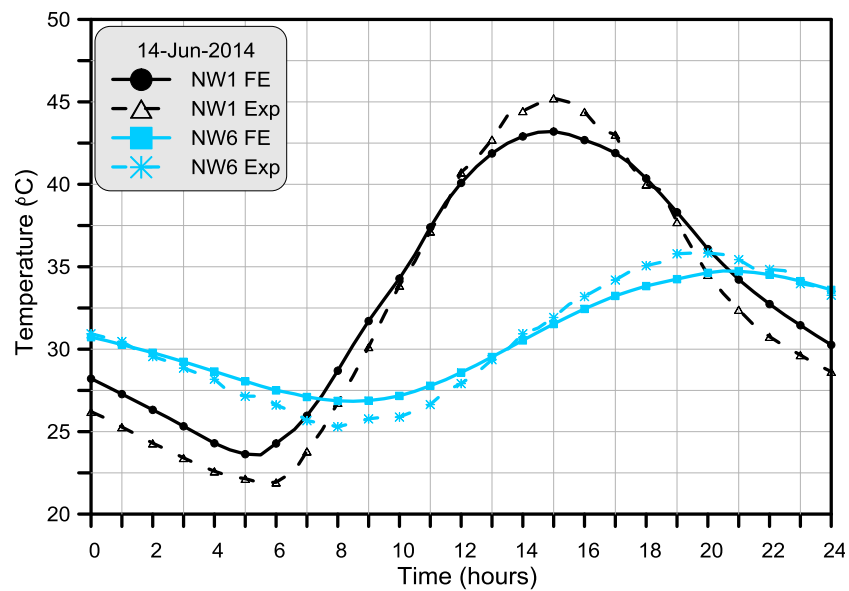


Figure 6.22 Hourly experimentally recorded and FE predicted temperatures at thermocouples NW1 and NW6 in 14-June-2014

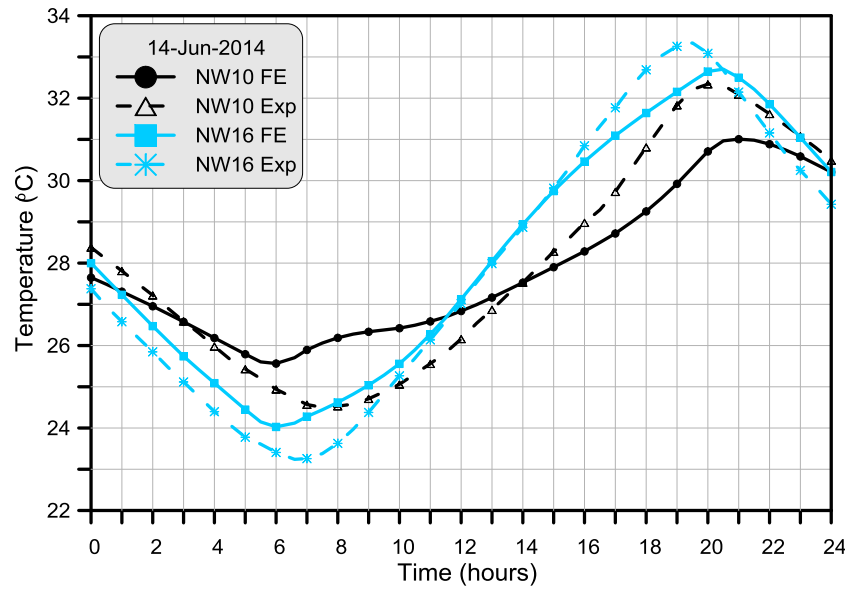


Figure 6.23 Hourly experimentally recorded and FE predicted temperatures at thermocouples NW10 and NW16 in 14-June-2014

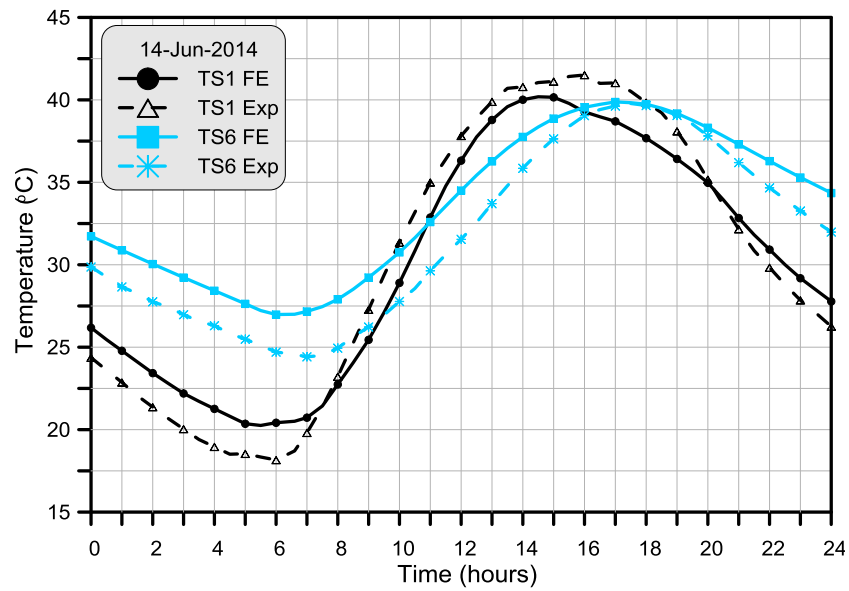


Figure 6.24 Hourly experimentally recorded and FE predicted temperatures at thermocouples TS1 and TS6 in 14-June-2014

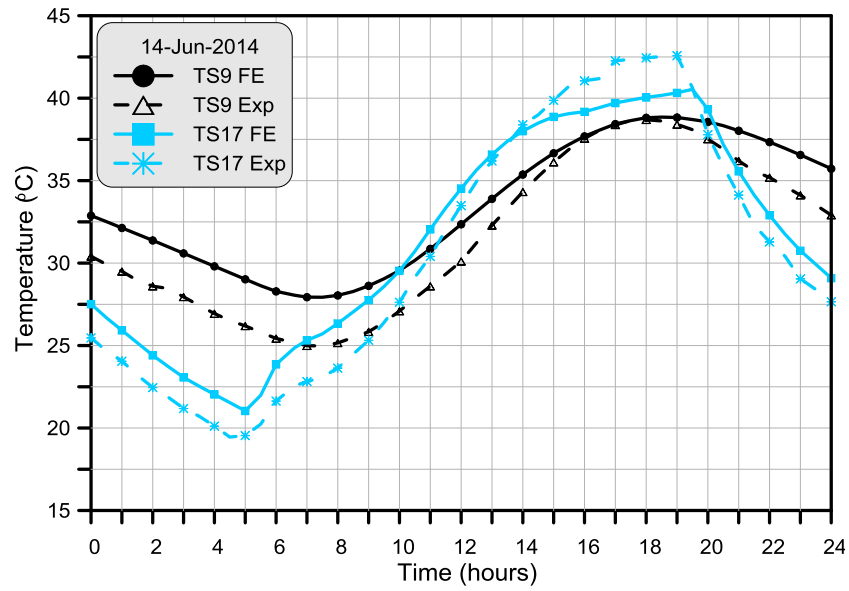


Figure 6.25 Hourly experimentally recorded and FE predicted temperatures at thermocouples TS9 and TS17 in 14-June-2014

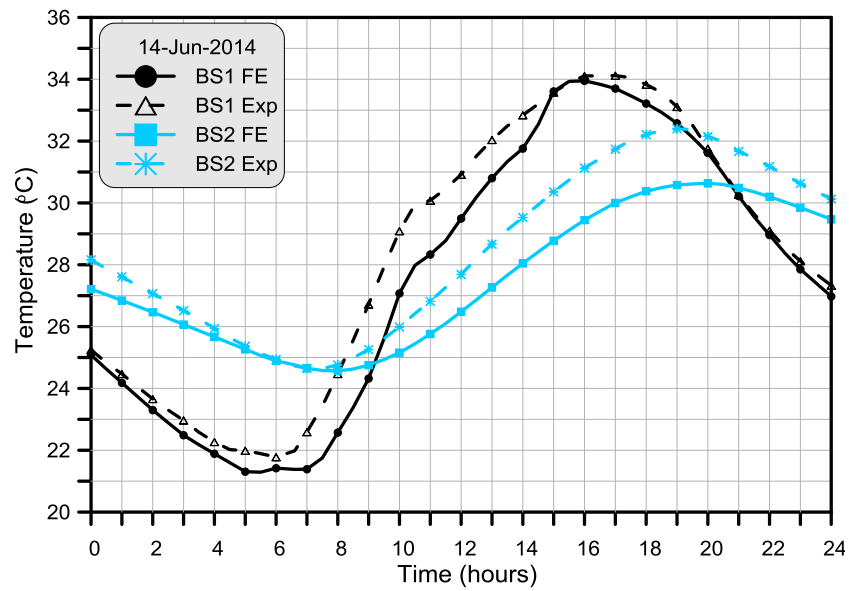


Figure 6.26 Hourly experimentally recorded and FE predicted temperatures at thermocouples BS1 and BS2 in 14-June-2014

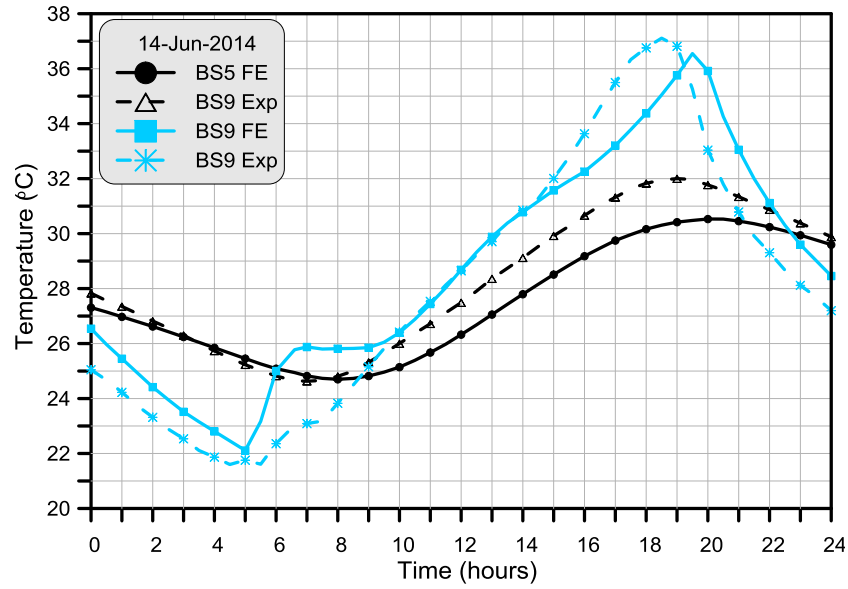


Figure 6.27 Hourly experimentally recorded and FE predicted temperatures at thermocouples BS5 and BS9 in 14-June-2014

In addition to the visualized thermocouples shown in Figures 6.4 through 6.27, Tables 6.1 to 6.4 lists the AAE, the MiAE, and the MaAE for all thermocouples passes through the centerlines of the SW, the NW, the TS, and the BS and for the three visualized days 10-July, 22-December, and 14-June. The tables show that for all thermocouples of the four groups, the AAE was in the range of 0.21°C to 2.16°C, while the MaAE ranged from 0.54°C to 3.2°C.

These ranges of MAE and MaAE reveal that the FE thermal analysis conducted in the current study could efficiently simulate the actual variations of temperature distributions in the experimental girder with reasonably low values of errors. Furthermore, the Figures from 6.4 to 6.27 illustrate that the conducted FE analysis could accurately model the fashion of temperature variation at each thermocouple location during the full studied time range.

Table 6.1 Minimum, maximum, and average absolute errors between the recorded and the FE predicted temperatures at each of the SW thermocouples along the 24 hours.

	SW 10-July-2013			SW 22-Dec-2013			SW 14-Jun-2014		
	MiAE	MaAE	AAE	MiAE	MaAE	AAE	MiAE	MaAE	AAE
SW1	0.041	2.894	0.932	0.086	2.538	1.377	0.013	2.777	1.342
SW2	0.071	1.780	0.807	0.003	2.593	1.445	0.015	2.881	1.137
SW3	0.264	1.686	0.829	0.051	2.286	1.255	0.000	2.532	0.988
SW4	0.294	1.907	0.950	0.082	2.220	1.127	0.005	1.950	0.939
SW5	0.000	2.404	1.100	0.004	2.284	1.411	0.011	1.718	0.856
SW6	0.008	1.860	0.885	0.329	2.356	1.430	0.012	1.869	0.827
SW7	0.031	1.751	0.894	0.060	2.357	1.220	0.025	2.345	1.056
SW8	1.008	2.240	1.501	0.038	2.133	0.994	0.817	2.046	1.411
SW10	0.558	2.244	1.257	0.042	2.269	1.353	0.594	1.943	1.203
SW12	0.020	1.687	0.989	0.025	2.533	1.564	0.031	1.683	1.053
SW13	0.015	1.899	0.811	1.371	1.676	1.530	0.001	1.791	0.909
SW14	0.002	0.914	0.371	1.259	1.685	1.475	0.019	2.417	1.000
SW15	0.094	0.830	0.493	1.138	1.523	1.360	0.006	2.629	1.001
SW16	0.051	1.098	0.579	1.202	1.838	1.410	0.010	2.794	0.999
SW17	0.009	0.849	0.390	0.623	1.389	1.181	0.004	2.683	0.955
SW18	0.032	1.258	0.578	0.233	1.389	1.032	0.056	2.809	0.995

Table 6.2 Minimum, maximum, and average absolute errors between the recorded and the FE predicted temperatures at each of the NW thermocouples along the 24 hours.

	NW 10-July-2013			NW 22-Dec-2013			NW 14-Jun-2014		
	MiAE	MaAE	AAE	MiAE	MaAE	AAE	MiAE	MaAE	AAE
NW1	0.245	2.244	0.946	0.368	2.132	1.112	0.103	2.508	1.469
NW2	0.262	1.437	0.936	0.610	2.177	1.413	0.060	2.529	1.163
NW3	0.051	1.681	0.833	0.344	1.968	1.174	0.048	2.310	1.149
NW4	0.028	1.483	0.708	0.463	1.937	1.004	0.024	2.151	1.083
NW5	0.055	1.362	0.622	0.058	1.542	0.735	0.043	1.578	0.816
NW6	0.022	1.508	0.680	0.012	1.394	0.665	0.049	1.569	0.738
NW7	0.017	1.443	0.686	0.014	1.109	0.443	0.009	1.691	0.744
NW8	0.043	2.026	1.026	0.007	1.043	0.460	0.019	1.742	0.775
NW10	0.019	2.332	1.186	0.014	0.883	0.416	0.004	1.906	0.829
NW12	0.022	2.591	1.385	0.001	0.635	0.294	0.054	2.188	0.985
NW13	0.028	2.421	1.193	0.019	0.726	0.290	0.054	2.422	1.078
NW14	0.006	1.884	0.991	0.034	0.632	0.314	0.011	1.781	0.764
NW15	0.113	0.975	0.531	0.055	1.134	0.548	0.008	1.509	0.671
NW16	0.061	0.921	0.577	0.008	1.665	0.637	0.013	1.130	0.562
NW17	0.151	1.103	0.685	0.028	1.741	0.653	0.005	0.780	0.356
NW18	0.025	1.154	0.614	0.004	1.606	0.706	0.006	1.469	0.461

Table 6.3 Minimum, maximum, and average absolute errors between the recorded and the FE predicted temperatures at each of the TS thermocouples along the 24 hours.

	TS 10-July-2013			TS 22-Dec-2013			TS 14-Jun-2014		
	MiAE	MaAE	AAE	MiAE	MaAE	AAE	MiAE	MaAE	AAE
TS1	0.011	2.810	1.244	0.184	2.565	1.266	0.064	2.446	1.573
TS3	0.059	2.604	0.981	0.008	2.519	1.448	0.198	2.884	1.837
TS5	0.007	2.967	0.895	0.144	2.384	1.605	0.126	2.893	1.874
TS6	0.204	2.467	1.073	0.000	2.273	1.084	0.048	3.075	1.860
TS7	0.023	2.557	1.112	0.155	2.542	1.180	1.007	3.202	2.164
TS9	0.018	2.575	1.120	0.013	2.324	1.000	0.000	2.949	1.915
TS11	0.030	2.386	1.105	0.005	2.546	1.026	0.651	2.979	2.125
TS12	0.196	2.517	1.075	0.008	2.655	0.980	0.588	3.006	2.106
TS13	0.042	3.200	0.975	0.656	2.400	1.551	0.036	2.015	1.093
TS15	0.019	2.915	0.864	0.038	2.584	1.671	0.076	2.398	1.430
TS17	0.117	2.768	1.229	0.025	2.541	1.274	0.094	2.698	1.702

Table 6.4 Minimum, maximum, and average absolute errors between the recorded and the FE predicted temperatures at each of the BS thermocouples along the 24 hours.

	BS 10-July-2013			BS 22-Dec-2013			BS 14-Jun-2014		
	MiAE	MaAE	AAE	MiAE	MaAE	AAE	MiAE	MaAE	AAE
BS1	0.227	1.991	0.902	0.250	2.099	1.064	0.029	2.397	0.772
BS2	0.321	1.600	0.850	0.012	0.613	0.320	0.004	1.844	0.953
BS3	0.530	1.600	1.000	0.011	0.999	0.521	0.007	1.817	0.877
BS5	0.263	1.429	0.760	0.001	0.540	0.247	0.025	1.667	0.789
BS7	0.002	1.288	0.563	0.009	0.573	0.211	0.004	1.776	0.759
BS8	0.041	1.131	0.513	0.008	0.711	0.298	0.010	1.412	0.647
BS9	0.013	1.601	0.613	0.017	1.740	0.702	0.024	2.880	1.280

6.4.2 Vertical Temperature Distributions at Specific Time Steps

Figures 6.28 to 6.42 show comparisons between the vertical temperature distributions along the centerlines of SW and NW and the 3D temperature distributions of the FE modeled box-girder at specific time steps in 10-July, 22-December, and 14-June. The selected time steps were 6:00 AM, 12:00 PM, and 6:00 PM. In general, the figures show that the predicted vertical temperature distributions try to follow the same variation trend of the recorded distributions from the experimental box-girder. Note that the number of records n in Equation 6.16 in this case is the number of the experimental thermocouples along the centerline of each web, which equals 16.

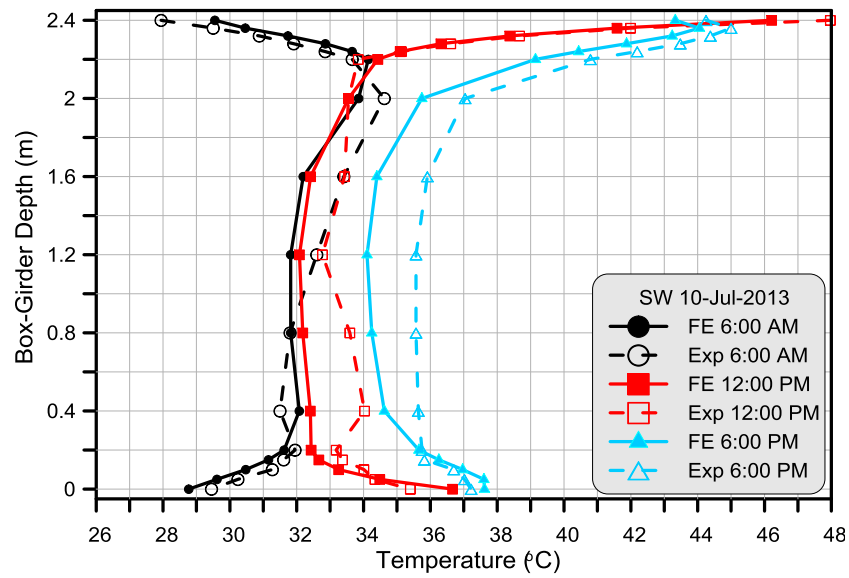


Figure 6.28 Experimentally recorded and FE predicted vertical temperature distributions along the centerline of the south-web in 10-July-2013

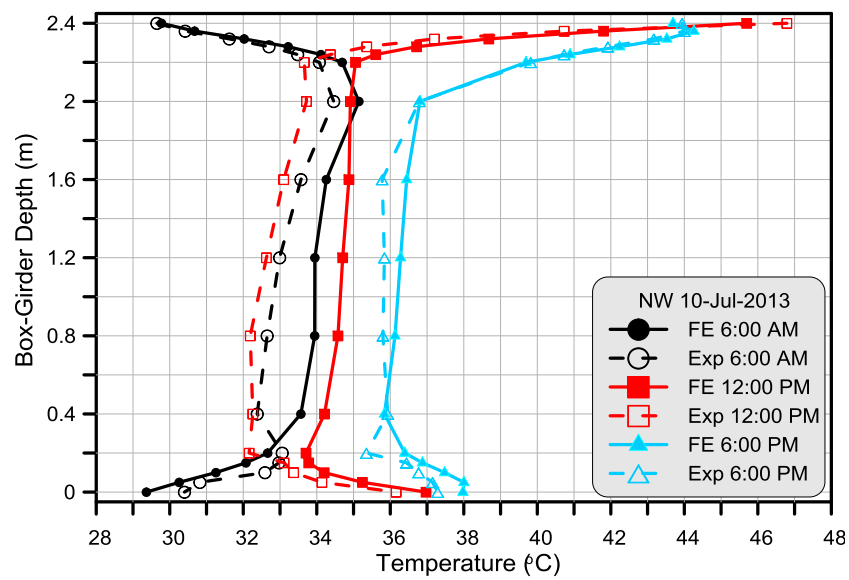


Figure 6.29 Experimentally recorded and FE predicted vertical temperature distributions along the centerline of the north-web in 10-July-2013

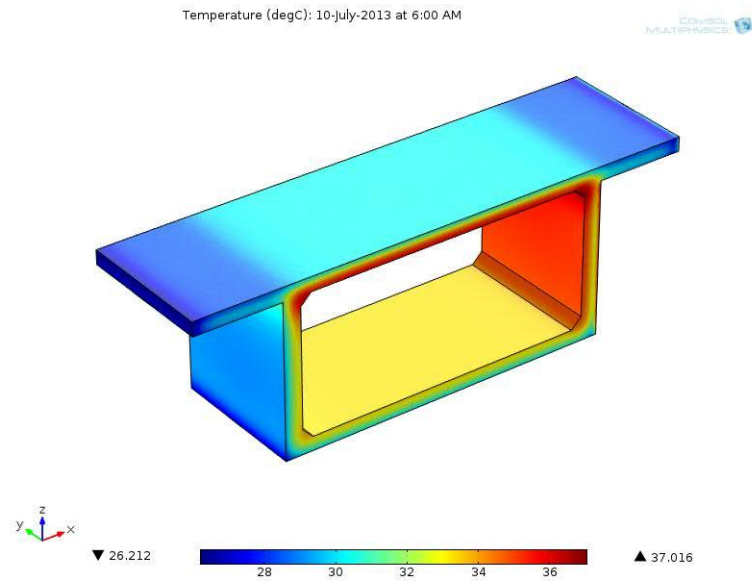


Figure 6.30 3D temperature distribution of the FE modeled box-girder at 6:00 AM in 10-July-2013

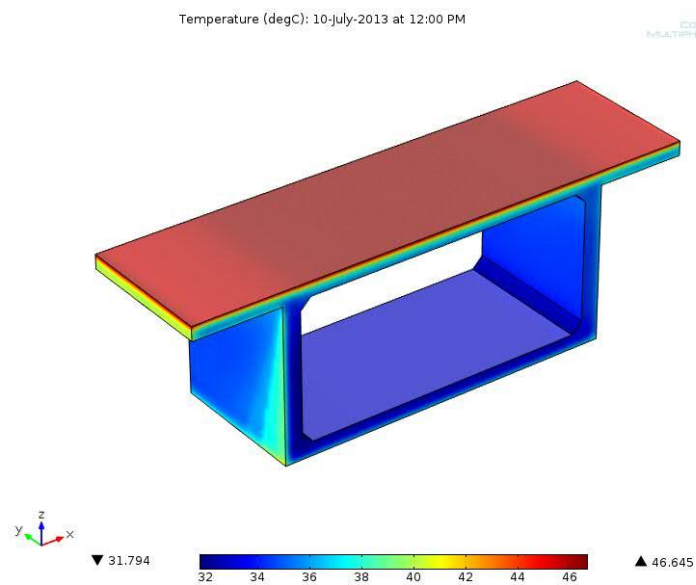


Figure 6.31 3D temperature distribution of the FE modeled box-girder at 12:00 PM in 10-July-2013

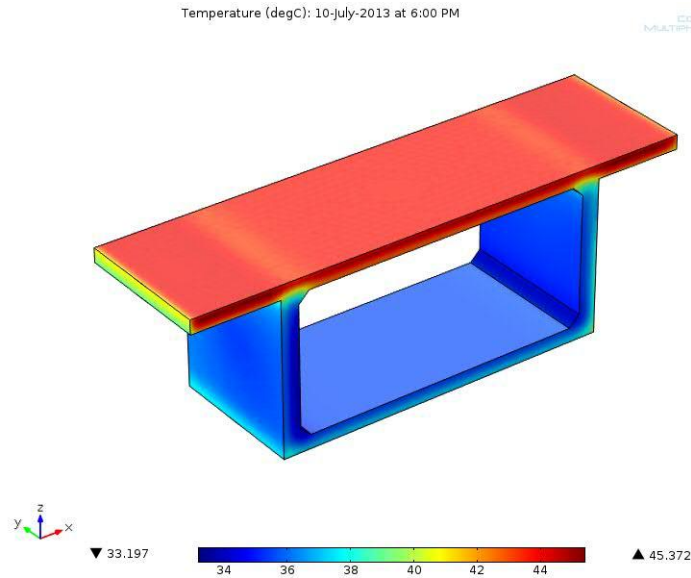


Figure 6.32 3D temperature distribution of the FE modeled box-girder at 6:00 PM in 10-July-2013

Figure 6.28 show the vertical temperature distributions along the centerline depth of the SW in 10-July. It is shown that the agreement between the predicted and the recorded distributions is good at all time steps. The AAE at 6:00 AM, 12:00 PM, and 6:00 PM was 0.79°C, 0.82°C, and 0.98°C, respectively, while the MaAE was 1.62°C, 1.89°C, and 1.75°C, respectively.

Figure 6.29 show the same temperature distributions for the NW in 10-July. Good agreement is also noticed for the NW temperature distributions. The AAE and MaAE along the depth of the NW at 6:00 AM were 0.71°C and 1.33°C, while at 12:00 PM and 6:00 PM, AAE and MaAE were 1.31°C and 2.38°C, and 0.44°C and 1.04°C. Thus, the highest deviations between the predicted and the recorded temperature distributions among the visualized three time steps and for both SW and NW were recorded at 12:00 PM. Figures 6.30 to 6.32 show the temperature distribution of the FE modeled box-girder at the three time steps.

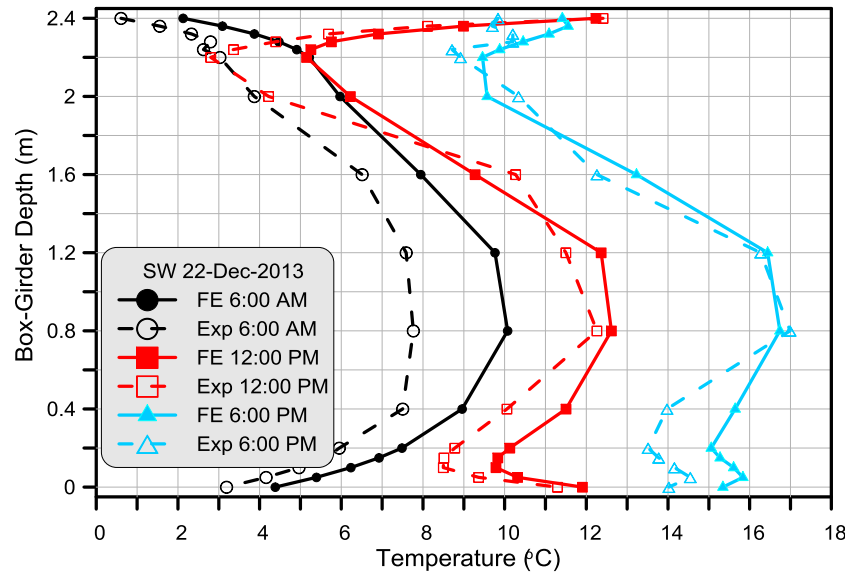


Figure 6.33 Experimentally recorded and FE predicted vertical temperature distributions along the centerline of the south-web in 22-December-2013

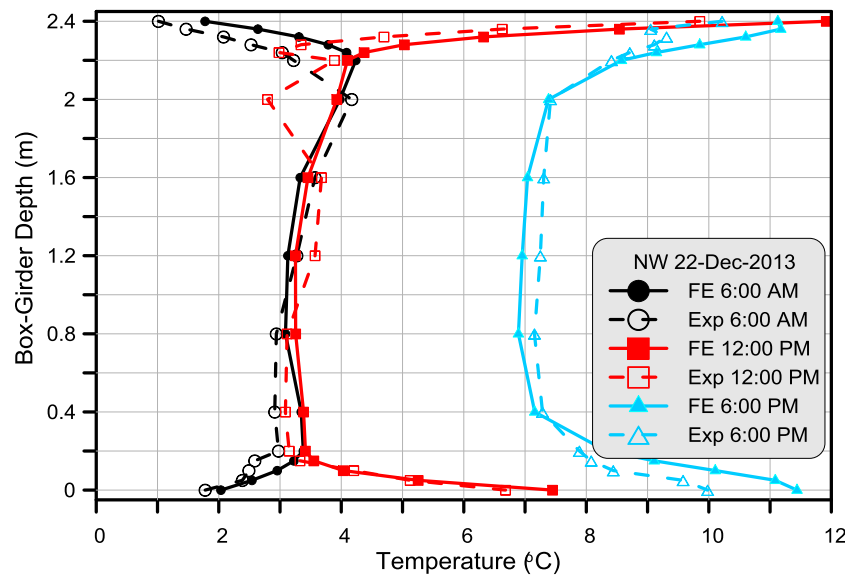


Figure 6.34 Experimentally recorded and FE predicted vertical temperature distributions along the centerline of the north-web in 22-December-2013

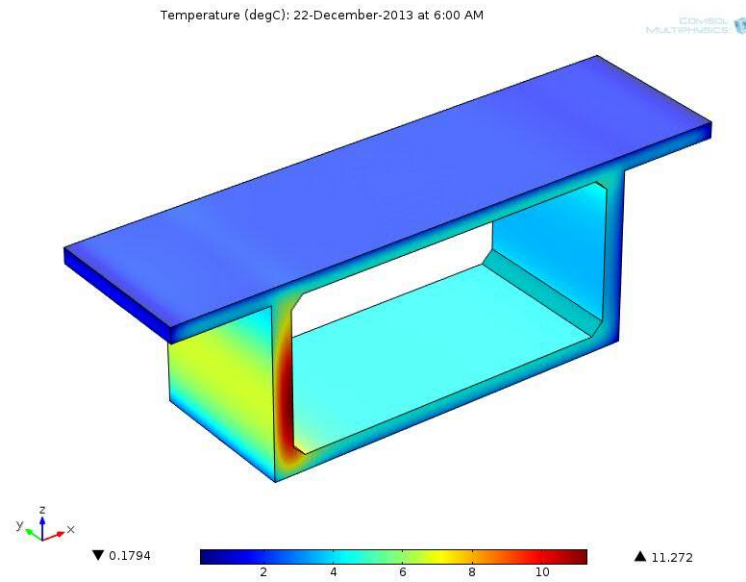


Figure 6.35 3D temperature distribution of the FE modeled box-girder at 6:00 AM in 22-December-2013

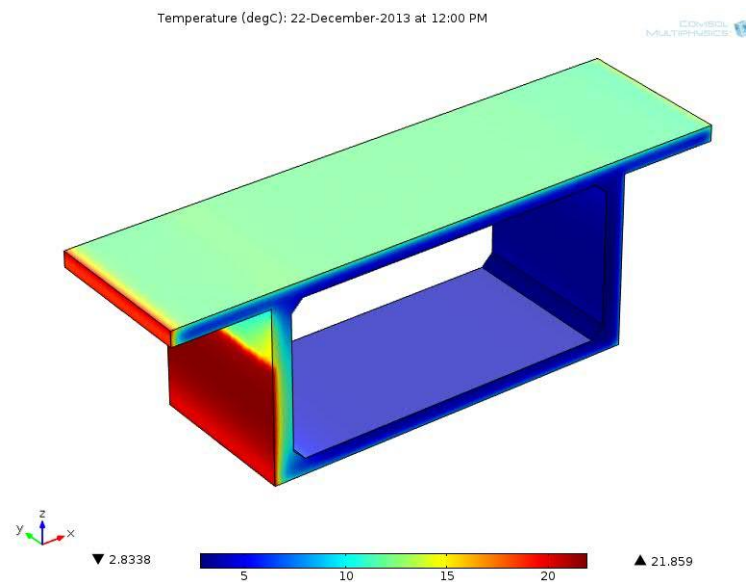


Figure 6.36 3D temperature distribution of the FE modeled box-girder at 12:00 PM in 22-December-2013

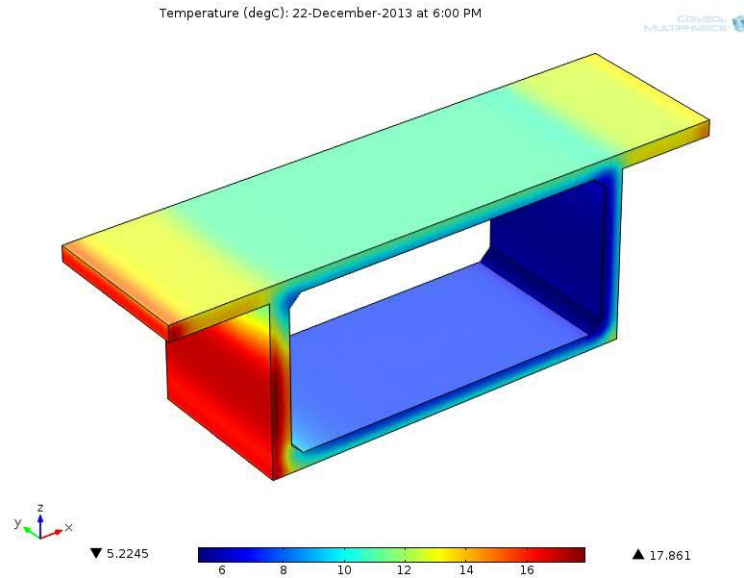


Figure 6.37 3D temperature distribution of the FE modeled box-girder at 6:00 PM in 22-December-2013

Figures 6.33 and 6.34 illustrate the vertical temperature distributions along SW and NW in 22-December, in which, good agreement is shown between the predicted and the recorded temperature distributions. The AAE for the three time steps was in the range of 1.07°C to 1.68°C for the SW, while it ranged from 0.61°C to 0.82°C for the NW. On the other hand, the MaAE for the SW ranged from 1.85°C to 2.34°C, while MaAE of the NW ranged from 1.26°C to 2.12°C. Thus, it can be noticed that in general, both SW and NW show good agreement in 22-December. However, NW distributions show better agreement than those along the depth of SW. The 3D views of the temperature distributions at the three selected time steps in 22-December are shown in Figures 6.35 to 6.37

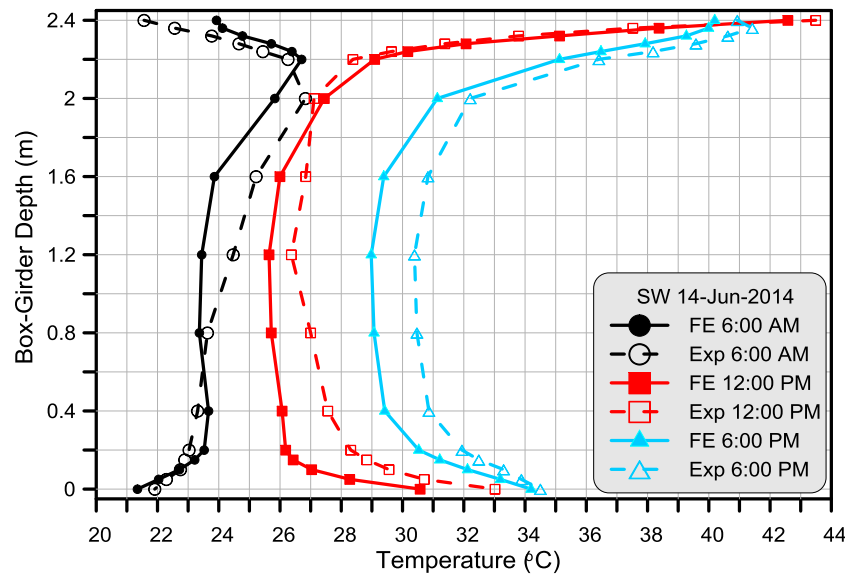


Figure 6.38 Experimentally recorded and FE predicted vertical temperature distributions along the centerline of the south-web in 14-June-2014

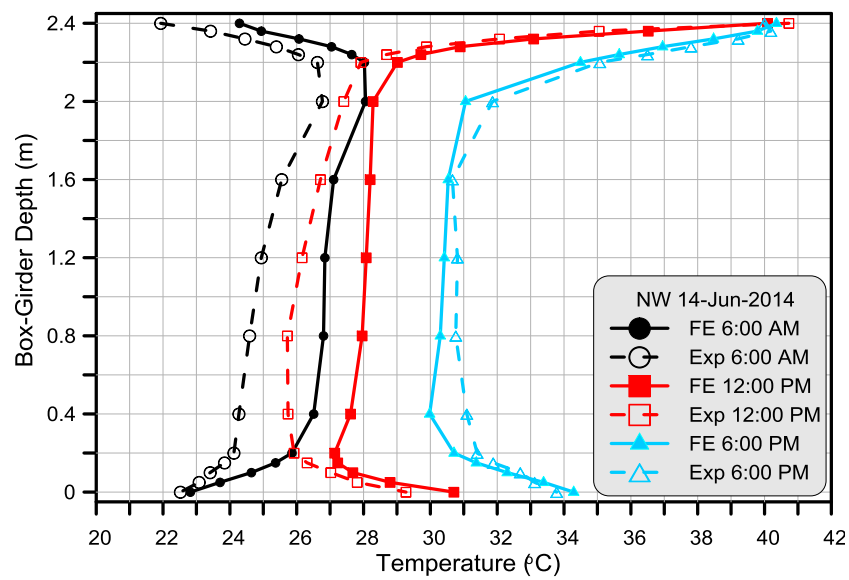


Figure 6.39 Experimentally recorded and FE predicted vertical temperature distributions along the centerline of the north-web in 14-June-2014

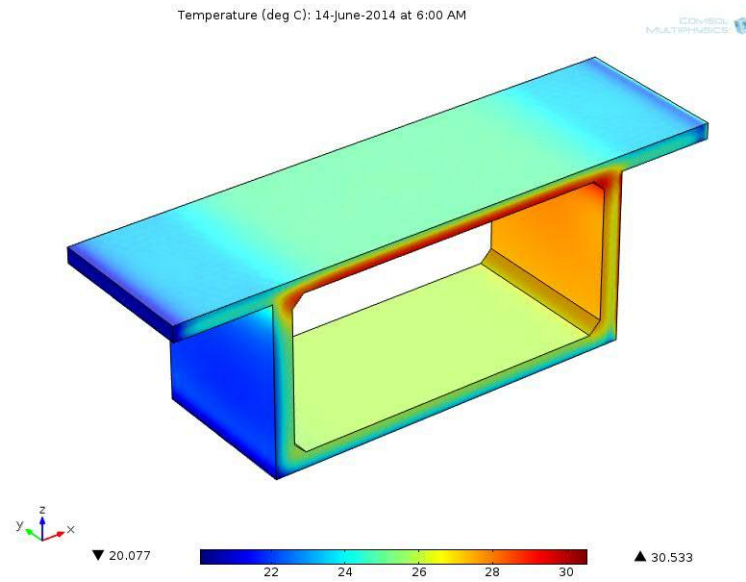


Figure 6.40 3D temperature distribution of the FE modeled box-girder at 6:00 AM
in 14-June-2014

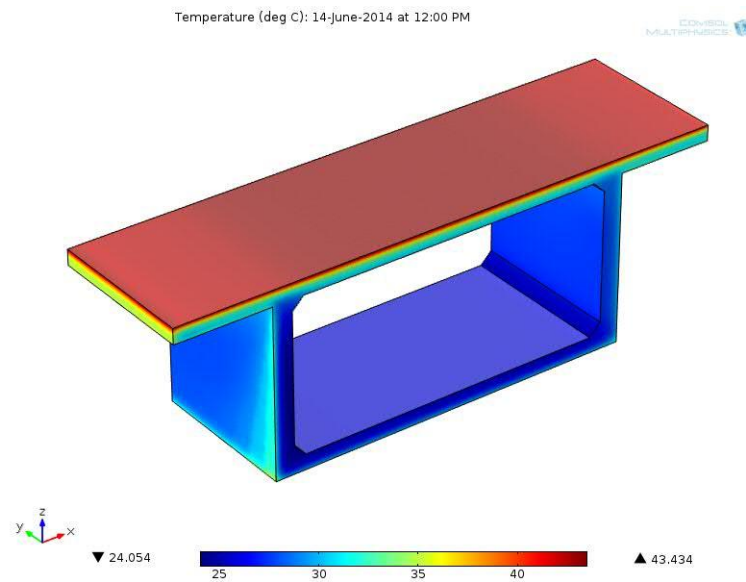


Figure 6.41 3D temperature distribution of the FE modeled box-girder at 12:00 PM
in 14-June-2014

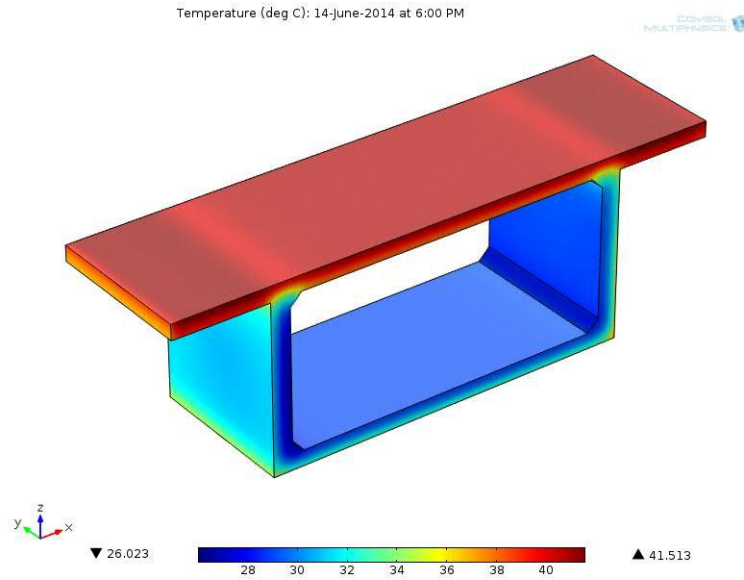


Figure 6.42 3D temperature distribution of the FE modeled box-girder at 6:00 PM in 14-June-2014

The vertical temperature distributions along the depth of the SW and the NW for 14-June are shown in Figures 6.38 and 6.39, while the 3D FE temperature distributions are shown in Figures 6.40 to 6.42. The AAE values for the three time steps 6:00 AM, 12:00 PM, and 6:00 PM were 0.86°C, 1.36°C, and 1.21°C, respectively for SW, while they were 1.52°C, 1.26°C, and 0.57°C, respectively for NW. On the other hand, the MaAE values at 6:00 AM, 12:00 PM, and 6:00 PM were 2.36°C, 2.52°C, and 1.7°C for SW, while MaAE values for the NW were 2.35°C, 2.23°C, and 1.11°C, respectively. Thus, the vertical temperature distributions in 14-June disclose the good agreement between the predicted and the recorded temperatures.

Tables 6.5, 6.6, and 6.7 list the AAE, the MaAE, and MiAE for temperature distributions along the SW and the NW at each hour in 10-July, 22-December, and 14-June. The AAE for all time steps and for the three days ranged from 0.3°C to 2.08°C, while MaAE ranged from 0.81°C to 3.2°C. The highest deviations were recorded along the NW in 14-June, while the lowest deviations were recorded along the NW on 10-July.

In general, the recorded maximum error between the experimental and the predicted temperatures was 3.2°C, while average errors have much lower values. Thus, it can be concluded that the FE thermal analysis conducted in this study could well model

the heat conduction in the experimental box-girder and could efficiently apply all boundary environmental thermal loads, so it could accurately simulate the heat transfer process in the concrete box-girder bridge segment.

Table 6.5 Minimum, maximum, and average absolute errors between the recorded and the FE predicted temperatures along the centerline of SW and NW for each time step in 10-Jul-2013

Time Step	SW 10-Jul-2013			NW 10-Jul-2013		
	MiAE	MaAE	AAE	MiAE	MaAE	AAE
12:00 AM	0.031	1.764	0.597	0.000	1.607	0.547
1:00 AM	0.008	1.793	0.617	0.021	1.561	0.551
2:00 AM	0.095	1.706	0.684	0.033	1.369	0.529
3:00 AM	0.006	1.639	0.662	0.069	1.022	0.529
4:00 AM	0.147	1.517	0.690	0.122	1.119	0.609
5:00 AM	0.146	1.389	0.732	0.133	1.151	0.632
6:00 AM	0.020	1.621	0.789	0.056	1.334	0.708
7:00 AM	0.070	1.561	0.832	0.150	1.838	0.912
8:00 AM	0.015	1.543	0.795	0.016	2.292	1.054
9:00 AM	0.205	1.517	0.816	0.313	2.591	1.314
10:00 AM	0.050	1.687	0.725	0.031	2.580	1.253
11:00 AM	0.017	1.899	0.768	0.068	2.529	1.297
12:00 PM	0.000	1.892	0.825	0.442	2.387	1.315
1:00 PM	0.061	2.213	0.931	0.525	2.244	1.317
2:00 PM	0.032	2.894	1.114	0.400	2.185	1.191
3:00 PM	0.160	2.249	1.118	0.205	1.828	0.988
4:00 PM	0.026	1.907	0.910	0.198	1.884	0.827
5:00 PM	0.041	1.733	0.865	0.022	1.584	0.761
6:00 PM	0.094	1.751	0.979	0.017	1.045	0.445
7:00 PM	0.023	1.846	0.940	0.025	0.816	0.327
8:00 PM	0.040	1.992	0.833	0.028	0.941	0.344
9:00 PM	0.065	2.257	0.998	0.006	0.971	0.298
10:00 PM	0.002	2.369	0.943	0.028	1.500	0.552
11:00 PM	0.009	2.404	0.980	0.056	1.437	0.489
12:00 AM	0.123	2.258	0.839	0.019	1.088	0.470

Table 6.6 Minimum, maximum, and average absolute errors between the recorded and the FE predicted temperatures along the centerline of SW and NW for each time step in 22-Dec-2014

Time Step	SW 22-Dec-2013			NW 22-Dec-2013		
	MiAE	MaAE	AAE	MiAE	MaAE	AAE
12:00 AM	0.647	1.983	1.349	0.012	1.345	0.605
1:00 AM	0.717	2.195	1.432	0.046	1.382	0.587
2:00 AM	0.822	2.179	1.473	0.096	1.463	0.603
3:00 AM	1.017	2.318	1.530	0.042	1.549	0.614
4:00 AM	1.126	2.375	1.572	0.054	1.592	0.627
5:00 AM	1.200	2.209	1.609	0.028	1.104	0.532
6:00 AM	1.193	2.308	1.681	0.146	1.260	0.610
7:00 AM	1.179	2.437	1.711	0.074	1.224	0.585
8:00 AM	1.158	2.538	1.815	0.007	2.122	0.740
9:00 AM	1.116	2.291	1.721	0.037	1.922	0.836
10:00 AM	1.156	2.593	1.772	0.033	2.078	0.848
11:00 AM	0.051	2.220	1.452	0.034	2.132	0.850
12:00 PM	0.173	2.346	1.199	0.039	2.065	0.815
1:00 PM	0.138	1.928	0.972	0.008	1.972	0.715
2:00 PM	0.038	1.847	0.913	0.051	1.844	0.730
3:00 PM	0.299	1.622	1.046	0.039	1.856	0.703
4:00 PM	0.086	1.668	0.948	0.027	1.957	0.675
5:00 PM	0.096	1.675	0.979	0.019	1.586	0.737
6:00 PM	0.171	1.854	1.069	0.032	2.125	0.828
7:00 PM	0.280	1.841	1.058	0.089	1.770	0.792
8:00 PM	0.131	1.624	0.992	0.058	1.363	0.692
9:00 PM	0.263	1.596	1.044	0.047	1.161	0.649
10:00 PM	0.102	1.603	1.132	0.150	1.242	0.659
11:00 PM	0.378	1.668	1.223	0.114	1.036	0.546
12:00 AM	0.679	1.875	1.314	0.004	1.023	0.494

Table 6.7 Minimum, maximum, and average absolute errors between the recorded and the FE predicted temperatures along the centerline of SW and NW for each time step in 14-June-2014

Time Step	SW 14-June-2014			NW 14-June-2014		
	MiAE	MaAE	AAE	MiAE	MaAE	AAE
12:00 AM	0.000	2.345	0.750	0.002	2.007	0.852
1:00 AM	0.026	2.180	0.730	0.134	2.001	0.969
2:00 AM	0.010	1.928	0.703	0.343	2.025	1.133
3:00 AM	0.001	1.760	0.673	0.549	1.920	1.225
4:00 AM	0.027	1.604	0.692	0.423	1.873	1.261
5:00 AM	0.128	1.497	0.702	0.091	2.058	1.311
6:00 AM	0.034	2.366	0.859	0.297	2.357	1.523
7:00 AM	0.031	2.425	1.023	0.170	2.842	1.896
8:00 AM	0.101	2.809	1.282	0.110	3.201	2.086
9:00 AM	0.111	2.749	1.577	0.028	3.160	1.931
10:00 AM	0.052	2.698	1.576	0.355	2.903	1.692
11:00 AM	0.245	2.785	1.574	0.244	2.592	1.456
12:00 PM	0.338	2.528	1.362	0.640	2.238	1.264
1:00 PM	0.015	2.432	1.136	0.402	1.831	0.978
2:00 PM	0.001	2.465	1.157	0.048	1.783	0.773
3:00 PM	0.025	2.777	1.178	0.115	2.025	0.711
4:00 PM	0.306	2.356	1.275	0.149	1.713	0.625
5:00 PM	0.437	1.833	1.212	0.028	1.120	0.495
6:00 PM	0.305	1.701	1.211	0.127	1.112	0.571
7:00 PM	0.078	1.869	1.204	0.112	1.539	0.662
8:00 PM	0.060	1.892	1.067	0.093	1.558	0.643
9:00 PM	0.015	1.830	0.859	0.020	1.829	0.601
10:00 PM	0.006	1.871	0.747	0.215	1.981	0.845
11:00 PM	0.082	1.884	0.681	0.427	1.806	1.009
12:00 AM	0.024	1.855	0.643	0.583	1.626	1.085

CHAPTER SEVEN

PARAMETRIC STUDIES

7.1 General

For design purposes, the extreme conditions and the most critical cases should be considered to satisfy the safe design requirements. As the geometry of the cross-section of the bridge's superstructure plays an important role in the thermal behavior, the geometrical parameters should be studied in details before performing extreme studies for the final design stages of the temperature gradients and the mean temperatures of the bridge.

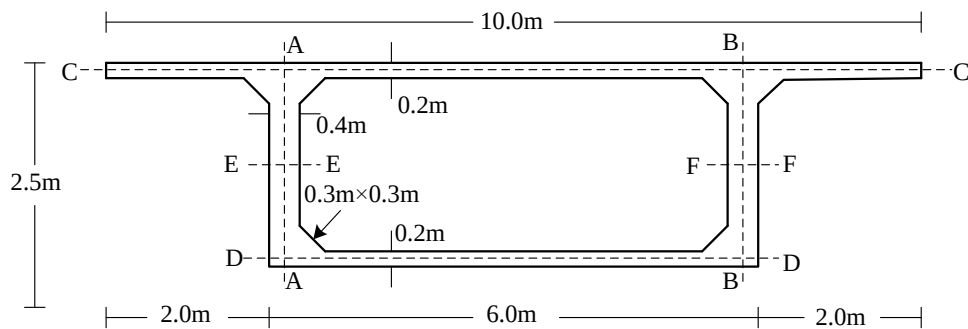


Figure 7.1 Dimensions of the basic box-girder cross-section for the parametric studies

To simulate the real and most frequently used geometries and the practical dimensions, in the current study, parametric studies were performed on the box-girder section shown in Figure 7.1. In addition to the thickness of the asphalt topping layer, six primary geometrical parameters were studied in this chapter, the orientation of the bridge, the overall depth of the box-girder, the width of the overhanging (cantilever) portions of the top slab, the thickness of the top slab, the thickness of the bottom slab, and the thickness of the webs. Four orientations were

investigated, the east-west (E-W), the north-south (N-S), the northeast-southwest (NE-SW), and the northwest-southeast (NW-SE). The box-girder depth was variable from 1 m to 12.5 m with seven different depths, 1 m, 2 m, 2.5 m, 5 m, 7.5 m, 10 m, and 12.5 m. The used cantilever widths were 0 m, 1 m, 2 m, and 3 m. Finally, four different thicknesses were used for the top slab, the bottom slab, and the webs, which were 0.2 m, 0.3 m, 0.4 m, and 0.5 m.

As shown in Figure 7.1, the temperature gradients were studied vertically along sections A-A and B-B along the centerlines of the webs. Moreover, the temperature gradients were studied laterally along the centerline of the top slab (section C-C), along the centerline of the bottom slab (section D-D), and across the thickness of the webs (sections E-E and F-F). The basic orientation of the longitudinal axis of the box-girder was E-W. Thus, the webs face the north and the south directions. The thermal conditions of Gaziantep in 2-June-2013 were the thermal loads used for the purposes of the parametric study.

7.2 Orientation of the Bridge's longitudinal axis

Figure 7.2 shows the positive vertical gradient along section A-A, in which the effect of the orientation of the bridge axis is clear on both the maximum gradient value and the gradient behavior along the box-girder depth. The figure shows clearly that the E-W orientation resulted in the maximum vertical positive temperature gradient, while the NW-SE resulted in the lowest one. The maximum temperature gradients at the top surface of the four orientations E-W, NE-SW, N-S, and NW-SE were 29°C, 25.6°C, 25.3°C, and 24.4°C, respectively. On the other hand, it is clear in Figure 7.2 that the temperature gradient along the top 1 m of the box-girder depth is obviously higher for the E-W direction than for other orientations.

Figure 7.3 shows that for the vertical negative temperature gradient in the same summer day, the opposite stands, where the E-W resulted in the lowest negative gradient of -6°C, while the NW-SE showed the highest negative temperature gradient of -6.8°C, which means that the temperature of the top surface of the E-W still higher than concrete interiors compared to the other orientations.

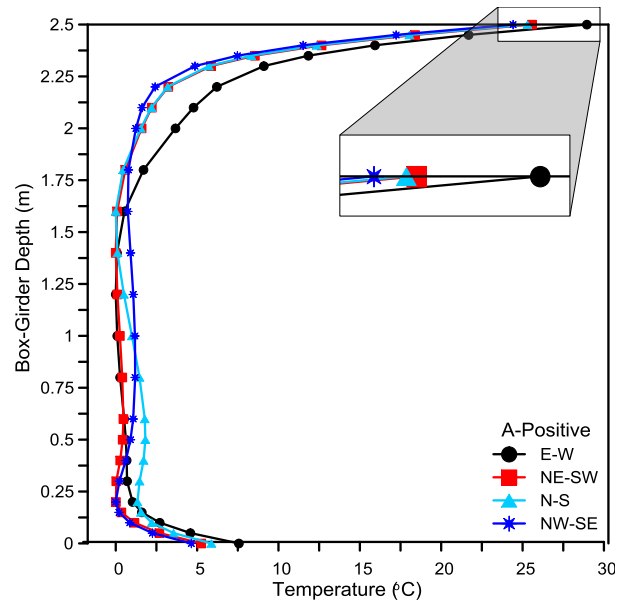


Figure 7.2 Positive temperature gradient distributions along section A-A for different bridge orientations

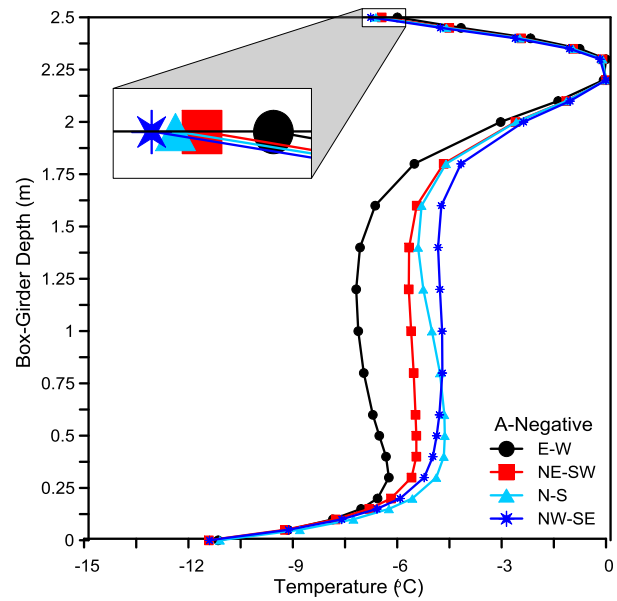


Figure 7.3 Negative temperature gradient distributions along section A-A for different bridge orientations

The positive temperature gradients along section B-B shown in Figure 7.4 show that the E-W still has almost the highest temperature gradient. However, the variation between the maximum gradient values is limited. The maximum temperature

gradients at the top surface for the four orientations E-W, NE-SW, N-S, and NW-SE were 27.5°C, 27 °C, 26.5°C, and 27.6°C, respectively.

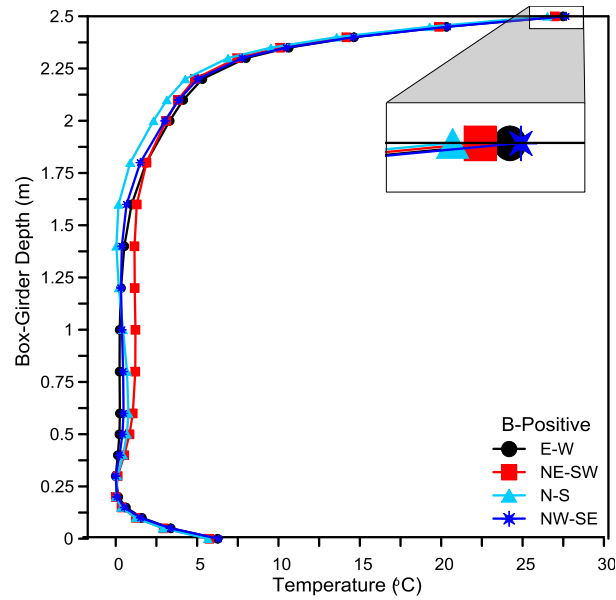


Figure 7.4 Positive temperature gradient distributions along section B-B for different bridge orientations

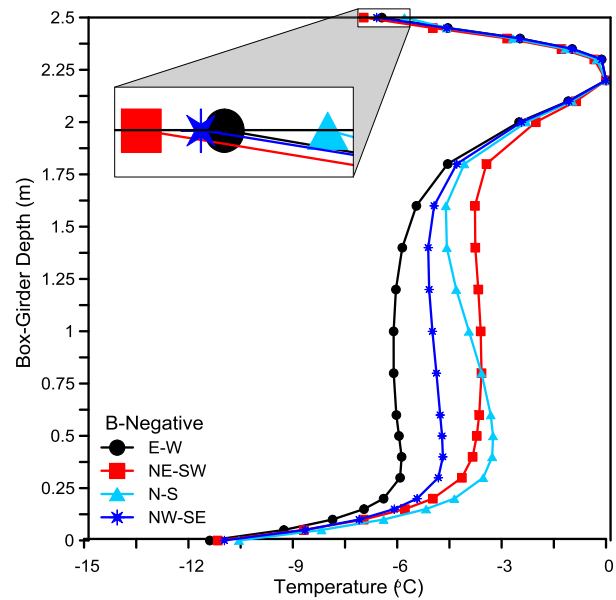


Figure 7.5 Negative temperature gradient distributions along section B-B for different bridge orientations

Figure 7.5 shows that for the night of 2-June along section B-B, the NW-SE and the NE-SW directions gave higher maximum negative vertical temperature gradients than the E-W and the N-S direction. The maximum negative temperature gradients at the top surface for the four orientations E-W, NE-SW, N-S, and NW-SE were -6.4°C , -7°C , -5.8°C , and -6.6°C , respectively for section B-B. Thus, it can be concluded that the E-W orientations results in the highest summer positive vertical temperature gradient, while for summer nights, the NE-SW gives the highest negative vertical temperature gradient.

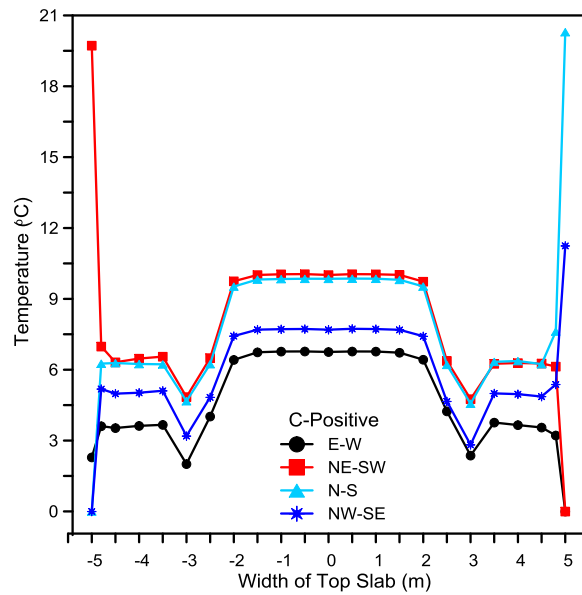


Figure 7.6 Positive temperature gradient distributions along section C-C for different bridge orientations

Figures 7.6 and 7.7 show the positive and negative lateral temperature gradients along the centerline of the top slab. As shown in Figure 7.6, the lateral gradient is significantly high for the orientations N-S and NE-SW compared to the E-W and NW-SE. The maximum lateral temperature gradients for the orientations N-S, NE-SW, NW-SE, and E-W were 20.3°C , 19.7°C , 11.2°C , and 6.8°C , respectively. As shown in Figure 7.6, the temperature of one of the slab edges (the west edge for the N-S and the northwest edge for the NE-SW) jumped significantly compared to the other points along the top slab. This jump occurred before the time of sunset where the sun strikes only from the north-west at very low altitude. Thus, the solar radiation concentrated on the vertical edge of the slab without having an effect on the top

surface. Note that the maximum positive lateral temperature gradients for the E-W and the NW-SE groups occurred between 3:00 PM and 5:00 PM.

Figure 7.7 shows that the N-S orientation also results in the largest negative lateral temperature gradient among the four orientations. During the early morning hours, the eastern edge receives considerable amount of heat from the low altitude sunrays after sunrise, while the top surface still not exposed to solar radiation, which results in maximum lateral negative gradient at the opposite (western) edge. The maximum negative gradient of the N-S direction was -18.7°C .

For the same reasons discussed for the lateral gradient along the top slab, Figures 7.8 and 7.9 show that the maximum positive and negative lateral temperature gradients along the bottom slab occurred along the N-S orientation. The maximum positive and negative lateral temperature gradients along the bottom slab were 22.4°C and -18.8°C , respectively.

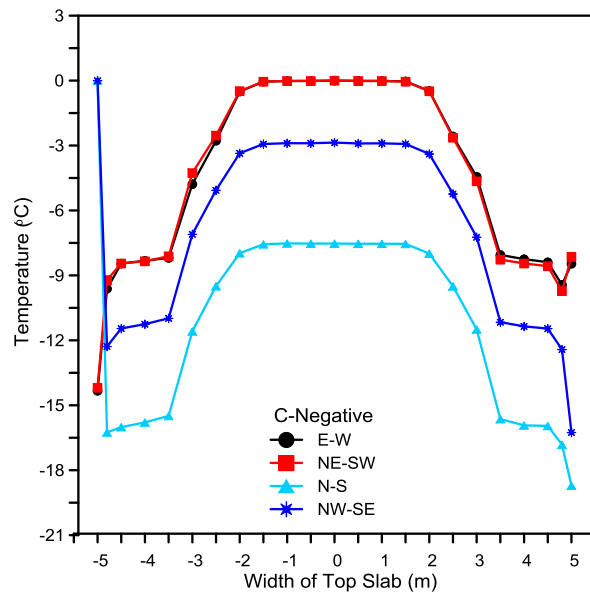


Figure 7.7 Negative temperature gradient distributions along section C-C for different bridge orientations

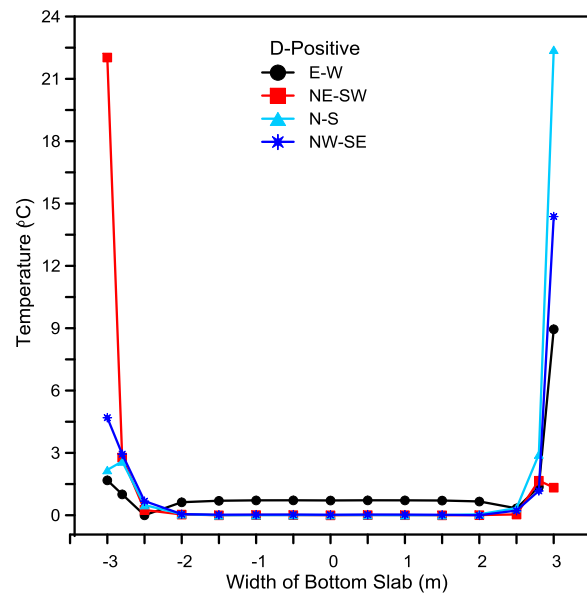


Figure 7.8 Positive temperature gradient distributions along section D-D for different bridge orientations

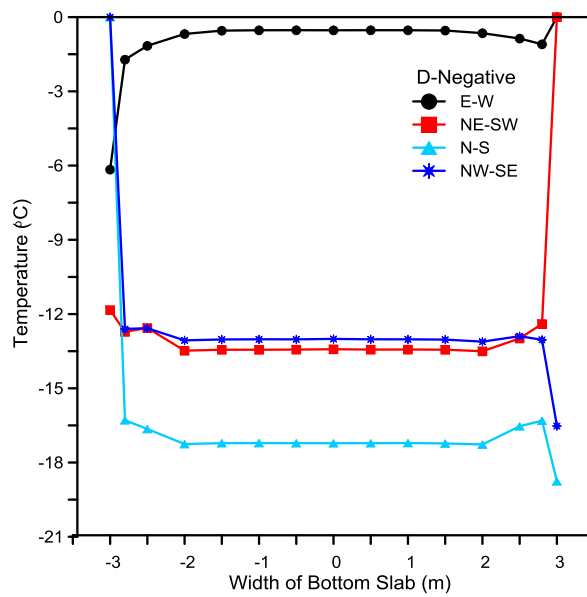


Figure 7.9 Negative temperature gradient distributions along section D-D for different bridge orientations

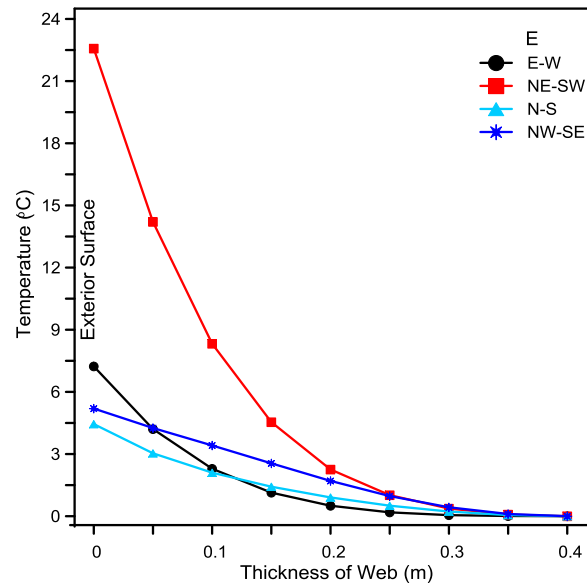


Figure 7.10 Positive temperature gradient distributions along section E-E for different bridge orientations

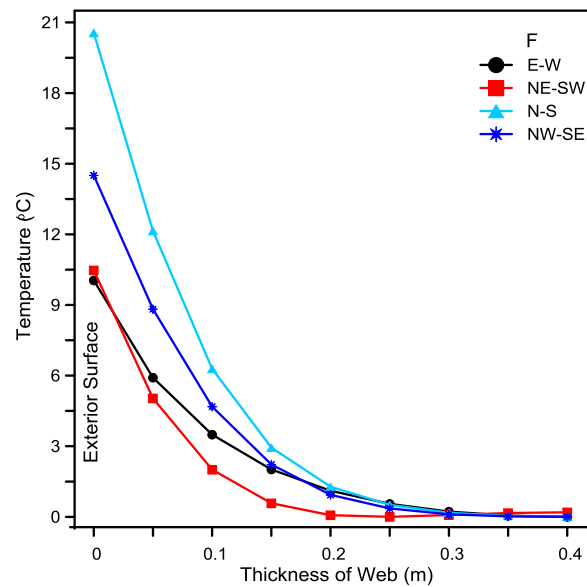


Figure 7.11 Positive temperature gradient distributions along section F-F for different bridge orientations

Figure 7.10 shows the positive temperature gradient across the web along section E-E. It is obvious that the NE-SW orientations resulted in the highest lateral gradient across this web. This can be attributed to the low altitude solar radiation on the exterior surface of this web (northwest surface) before the sunset, which causes a

quick rise in temperature due to the concentrated sunrays, which are almost perpendicular on the web. The maximum lateral temperature gradient for the NE-SW orientation was 22.6°C, which occurred at 6:40 PM. The maximum lateral gradients for the other orientations ranged from 4.4°C to 7.2°C and occurred between 1:20 PM and 2:20 PM. For the same reason, the N-S orientation resulted in the maximum lateral temperature gradient across the western web (section F-F) at 6:40 PM, which was 20.6°C as shown in Figure 7.11.

As a result, it can be concluded that the orientations N-S and NE-SW, in which one of the webs faces the sunrise and the other one faces the sunset result in the highest lateral temperature gradients both along the top and bottom slabs and across the webs.

7.3 Depth of the Box-Girder

Figures 7.12 and 7.14 show the effect of the box-girder depth on the vertical positive temperature gradients, while Figures 7.13 and 7.15 show the effect of the box-girder depth on the vertical negative temperature gradients along the south web (section A-A) and the north web (section B-B). The maximum positive temperature gradient increased as the depth increased but with small increments. The maximum positive temperature gradients at the top surface along section A-A were 27.5°C, 28.6°C, 29°C, 29.1°C, 29.2°C, and 29.2°C for box-girder depths of 1 m, 2 m, 2.5 m, 5 m, 7.5 m, and 10 m. For the 12.5 m, the maximum gradient was 29.1°C. Thus, it can be said that the box-girder depth has a small effect on the value of the maximum positive temperature gradient for depths shallower than 5m, while it becomes ineffective for deeper box-girders. Similar sequence of results were recorded for section B-B but with lower gradients ranging from 26.3°C to 27.8°C as shown in Figure 7.14.

Another important note is that the point of zero gradient from the top surface was 1.2 m for box-girder depths from 2 m to 10 m, while it was 0.8 m for box-girder depth of 1 m and 1.5 m for box-girder depth of 12.5 m as shown in Figure 7.12.

Figures 7.13 and 7.15 show that the depth of box-girder has no effect on the negative temperature gradient in summer. Both the maximum gradient value and the behavior were almost the same for all groups. The maximum negative gradient along section

A-A at the top surface was in the range of -6°C to -6.1°C , while it was in the range of -11.2 to -11.2 at the bottom surface. Furthermore, the point of zero gradient along section A-A was 0.2m below the top surface for all box-girder depths.

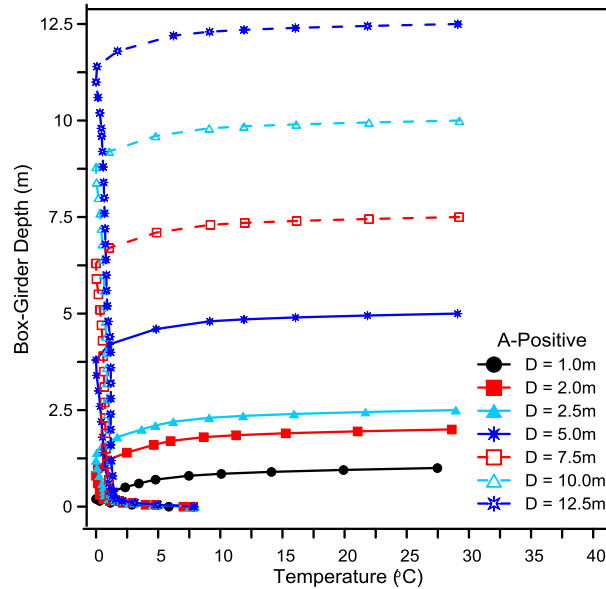


Figure 7.12 Positive temperature gradient distributions along section A-A for different box-girder depths

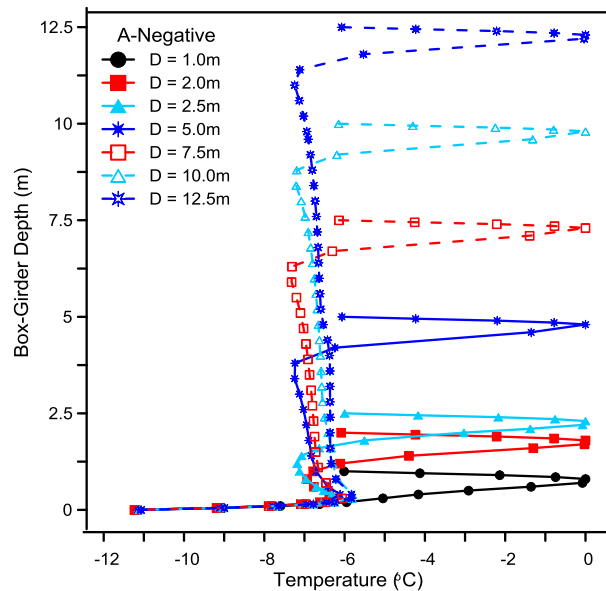


Figure 7.13 Negative temperature gradient distributions along section A-A for different box-girder depths

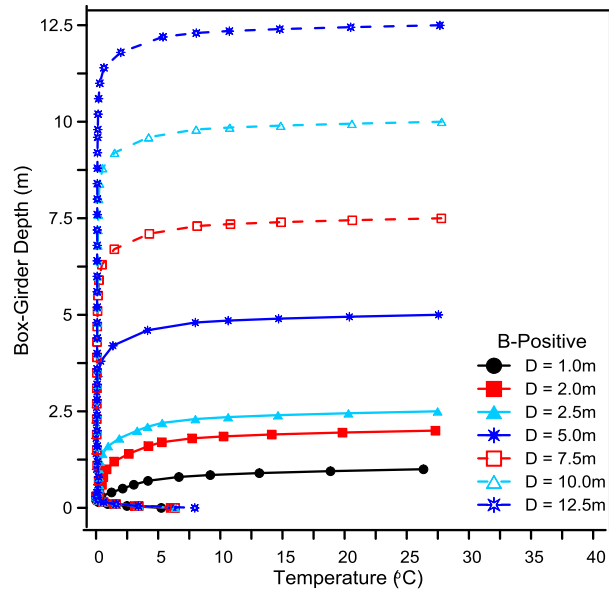


Figure 7.14 Positive temperature gradient distributions along section B-B for different box-girder depths

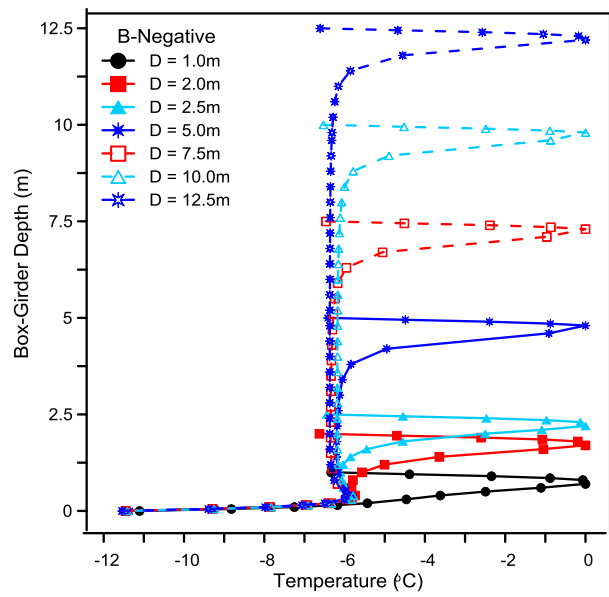


Figure 7.15 Negative temperature gradient distributions along section B-B for different box-girder depths

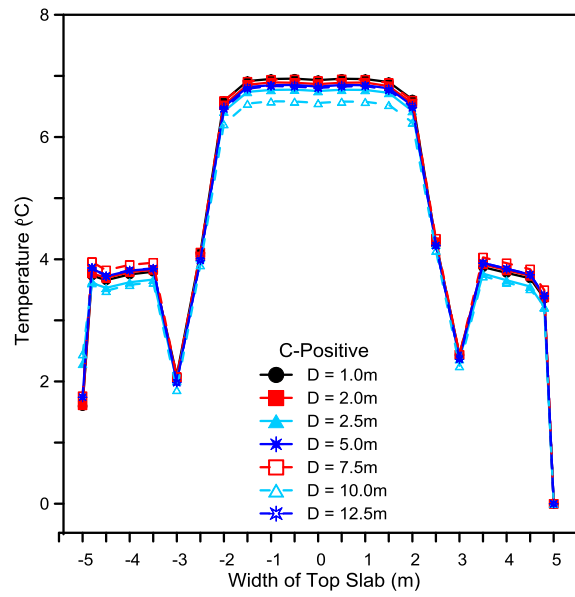


Figure 7.16 Positive temperature gradient distributions along section C-C for different box-girder depths

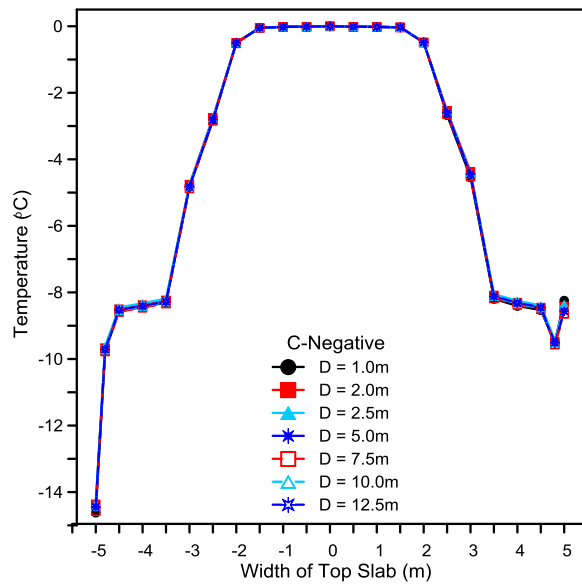


Figure 7.17 Negative temperature gradient distributions along section C-C for different box-girder depths

It is obvious from the observation of Figures 7.16 and 7.17 that the box-girder depth has no significant effect on the lateral temperature gradients along the top slab. For all of the box-girder depths, the maximum positive gradient ranged from 6.6°C to

6.9°C, while the maximum negative temperature gradient was in the range of -14.3°C to -14.6°C.

Along the bottom slab (section D-D), excluding the box-girder depth of 1 *m*, the temperature gradient behaviors were almost the same for all groups, both for the positive and the negative temperature gradients as shown in Figures 7.18 and 7.19. The temperature along the bottom slab was almost stable along the interior widths for box-girder depth of 1 *m* as shown in Figure 7.18. This can be attributed to the shading effect of cantilever slabs, where as the depth was shallow, the whole area of the webs were almost shaded, which resulted in temperature stabilization and hence lower gradients.

The lower interior temperatures for the 1 *m* depth group led to lower uniform gradient along the mid width of the bottom slab after the night cooling period compared to the edges, which was cooled faster as shown in Figure 7.19.

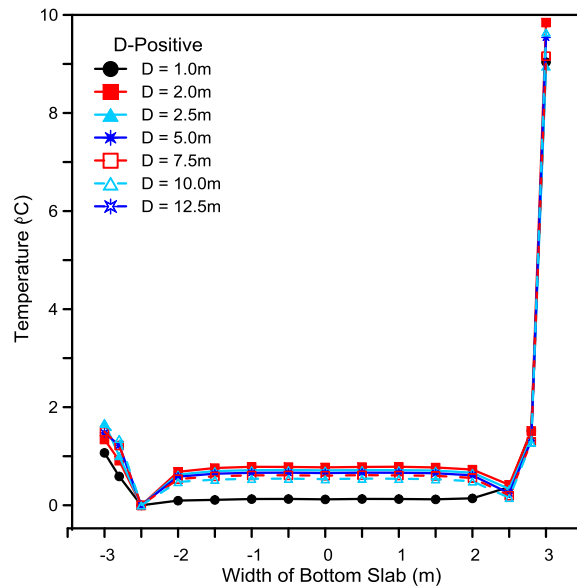


Figure 7.18 Positive temperature gradient distributions along section D-D for different box-girder depths

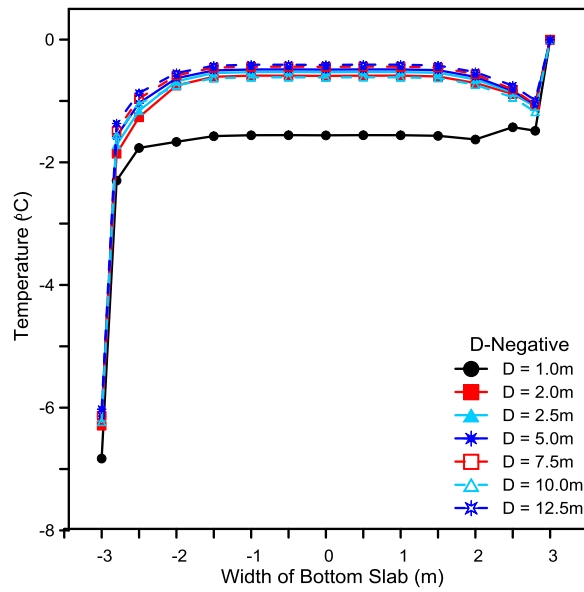


Figure 7.19 Negative temperature gradient distributions along section D-D for different box-girder depths

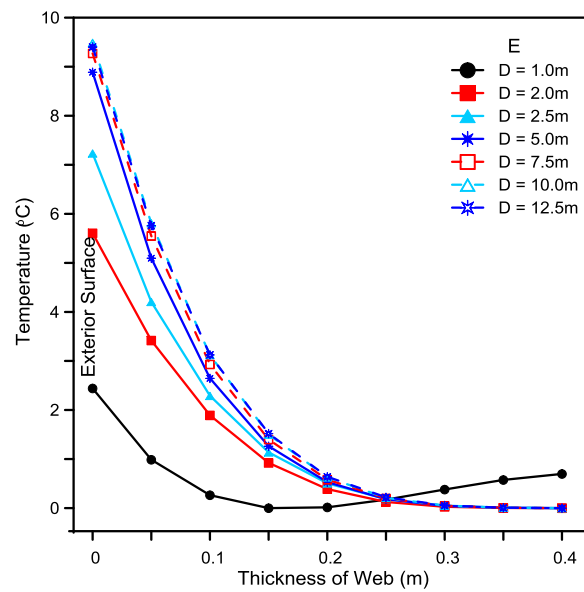


Figure 7.20 Positive temperature gradient distributions along section E-E for different box-girder depths

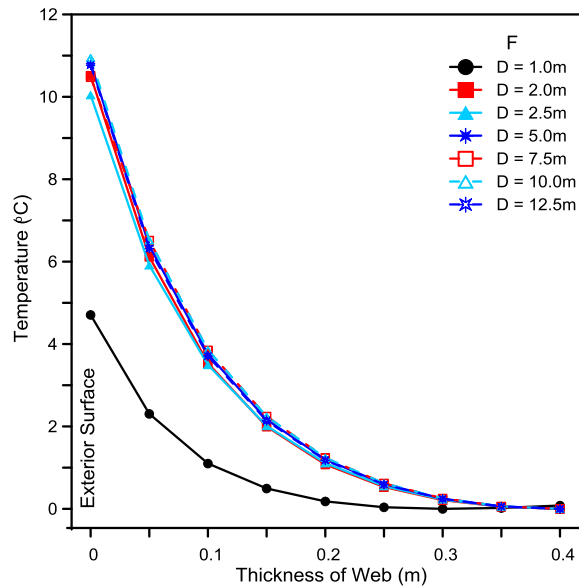


Figure 7.21 Positive temperature gradient distributions along section F-F for different box-girder depths

The effect of the box-girder depth is clear on the lateral temperature gradient across the south web (section E-E) shown in Figure 7.20. As the box-girder depth decreases, the lateral gradients decrease due to the effect of shadowing from the cantilever portions. Where the shading depth increase with the decrease of the box-girder depth, hence the time period along which the central area of the web (around section E-E) is shaded increases.

The maximum lateral temperature gradients across the south web were 2.4°C, 5.6°C, 7.2°C, 8.9°C, 9.3°C, 9.5°C, and 9.4°C for box-girder depths of 1 m, 2 m, 2.5 m, 5 m, 7.5 m, 10 m, and 12.5 m, respectively. It is clear that as the depth exceeds 5.0 m, the effect becomes smaller and diminishes after 10 m because the central depth of the web becomes completely not shaded during the midday hot hours for such depths.

The maximum temperature gradients across the south web occurred between 1:40 PM and 2:40 PM, therefore the shading effect was essential. However, across the north web (section F-F), which faces the sunset, the maximum gradient occurred between 6:20 PM and 6:40 PM (close to sunset). Thus, shading effect is minimal, where sunrays strikes at low angles, therefore the effect of the box-girder depth beyond 1 m was limited as shown in Figure 7.21.

In general it was recorded that the lateral temperature gradients across the north web were higher than their corresponding gradients across the south web. The maximum lateral temperature gradients across the north web for box-girder depths of 1 *m*, 2 *m*, 2.5 *m*, 5 *m*, 7.5 *m*, 10 *m*, and 12.5 *m* were 4.7°C, 10.5°C, 10°C, 10.8°C, 10.5°C, 10.9°C, and 10.8°C, respectively.

7.4 Width of the Cantilever Portions of the Top Slab

Figures 7.22 through 7.25 show clearly that the width of cantilever portions of the top slab has no direct impact on the values of vertical maximum positive and negative temperature gradients along both webs. The temperature gradients at the top surface were almost equal for the four groups with cantilever widths of 1 *m*, 2 *m*, and 3 *m*. However, as shown in Figure 7.22, the absence of cantilever portions (cantilever width = 0 *m*) reduced the maximum positive temperature gradient slightly by about 1.5°C. The maximum vertical positive temperature gradients along the south web (section A-A) were 27.4°C, 29.2°C, 29°C, and 28.9°C for cantilever width (*Cw*) of 0 *m*, 1 *m*, 2 *m*, and 3 *m*, respectively. Moreover, both the positive and the negative gradients were lower for the zero cantilever width along the depth of the south web (section A-A) and the north web (section B-B) as shown in Figures 7.22 through 7.25.

An explanation of this result is that the absence of the cantilever portion has omitted the shading effect on the webs or parts of which, thus increased the heating of the exterior faces of the webs, which results in higher temperatures in the interiors of the concrete webs, leading to lower difference between the temperatures of the top surface and the interiors.

As shown in Figures 7.22 through 7.25, the gradients at the bottom surface of the girder along the sections A-A and B-B were also lower for the box-girder with no cantilever portions than for the other groups. This can be attributed again to the same reason discussed above.

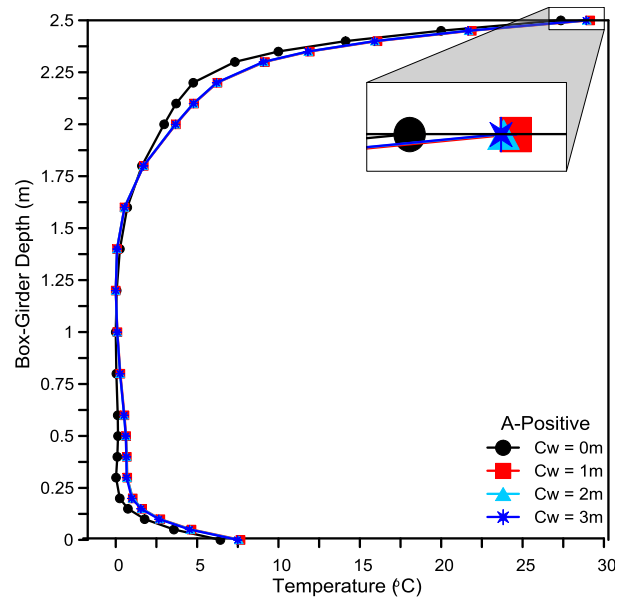


Figure 7.22 Positive temperature gradient distributions along section A-A for different cantilever widths

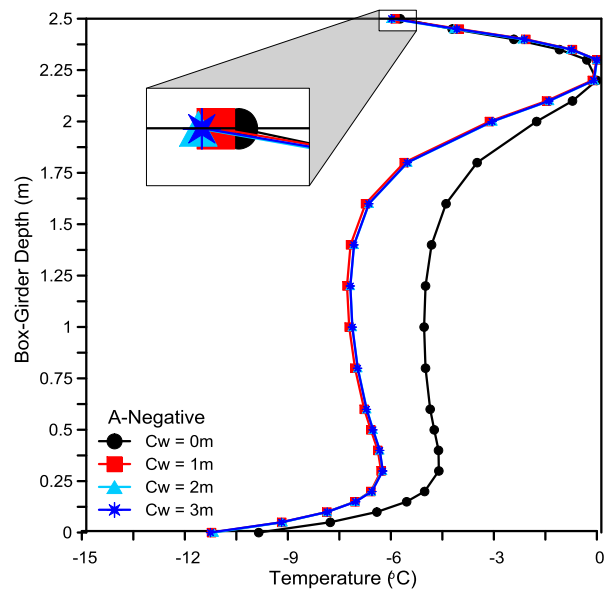


Figure 7.23 Negative temperature gradient distributions along section A-A for different cantilever widths

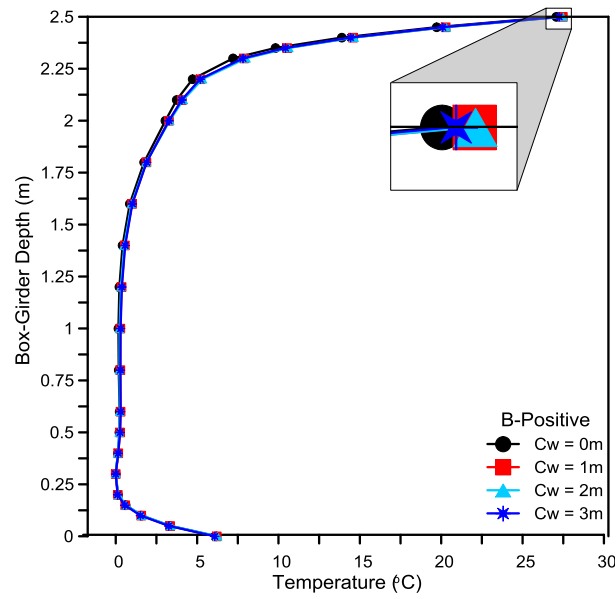


Figure 7.24 Positive temperature gradient distributions along section B-B for different cantilever widths

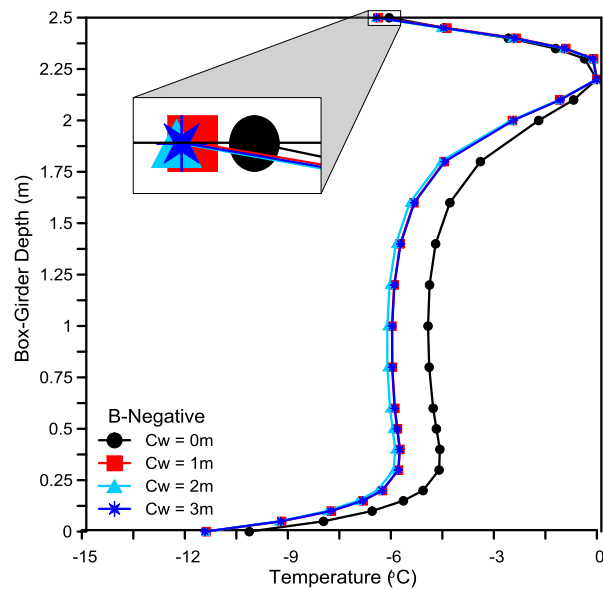


Figure 7.25 Negative temperature gradient distributions along section B-B for different cantilever widths

Figure 7.26 shows that the width of the cantilever portion of the top slab has no significant effect on the lateral temperature gradient along the top slab, except that the uniform temperature gradient along the mid-half of the top slab width was higher for the case of zero cantilever width. This is an expected result, since the absence of

the cantilevers increases the area of the surfaces that are exposed to solar radiation around this region, thus results in a global increase in the temperature of this region, which leads to higher uniform gradient. Figure 7.26 shows that the gradients along the interior width and along the outer cantilevers are almost equal for the rest three groups.

Figure 7.27 shows that the maximum lateral negative gradient for the box-girder without cantilever portions was also lower than other group, this can be attributed to the decrease of cooling variations among the different parts of the top slab due to the absence of the cantilever portions, which led to more uniform temperatures and hence lower gradients.

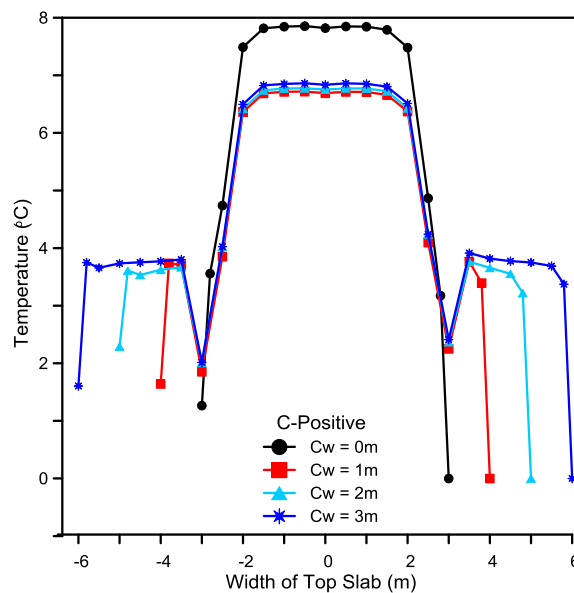


Figure 7.26 Positive temperature gradient distributions along section C-C for different cantilever widths

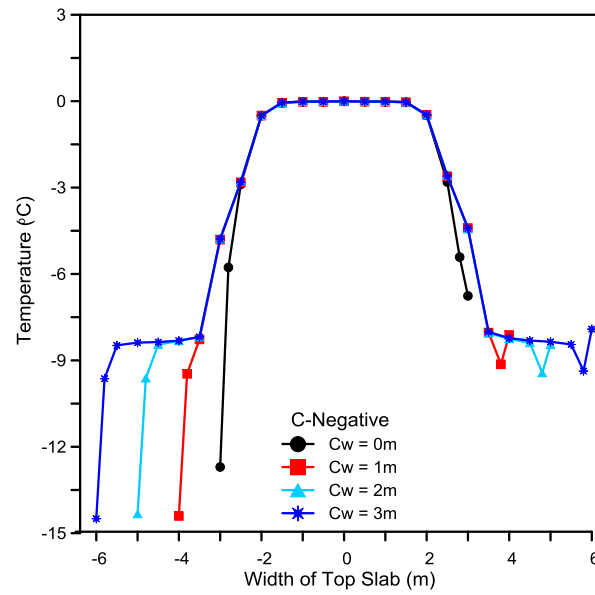


Figure 7.27 Negative temperature gradient distributions along section C-C for different cantilever widths

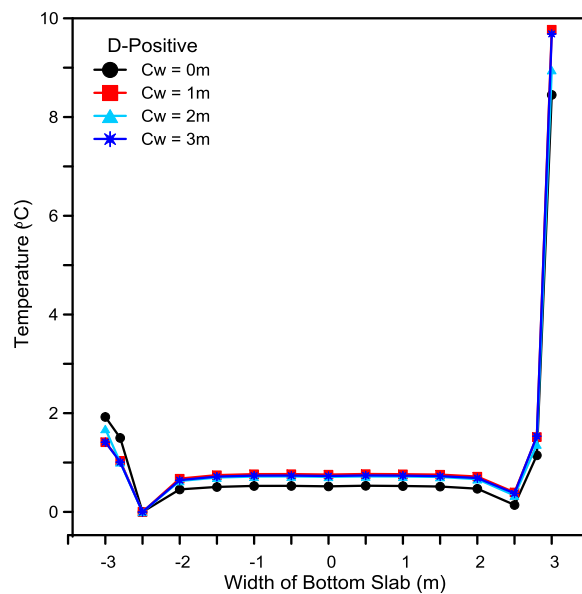


Figure 7.28 Positive temperature gradient distributions along section D-D for different cantilever widths

Figure 7.28 shows that the effect of the width of the cantilever portions on the positive lateral temperature gradients along the bottom slab is minimal. This result can be attributed to the location of the bottom slab edges compared to the cantilever

portions, thus within the studied range of cantilever widths, the shading effect still negligible because the web edges of the bottom slab still mostly not shaded.

The negative lateral gradient along the bottom slab (section D-D) show higher dependency on the width of cantilever portion than the positive gradient shows. The box-girder with cantilever portion of 3 m showed the highest negative temperature gradient of -6.9°C , while the box-girder without cantilever portions showed the lowest, which was -6°C as shown in Figure 7.29. The same effect stands along the interior width of the bottom slab as shown in the figure, however in both cases, the difference between the gradients was lower than 1°C .

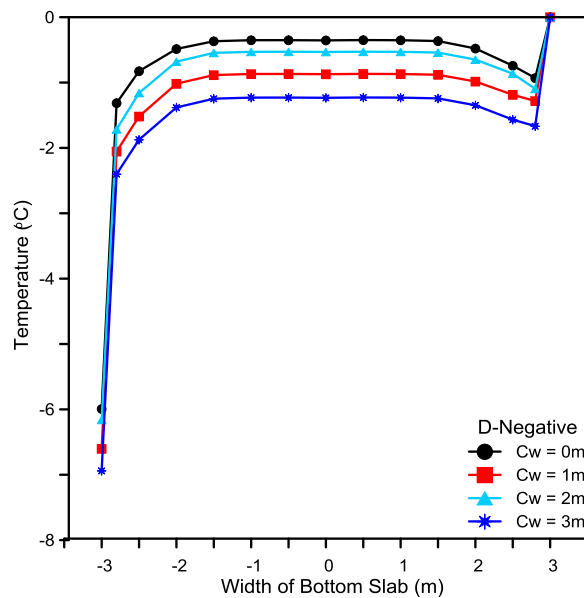


Figure 7.29 Negative temperature gradient distributions along section D-D for different cantilever widths

The degree of dependency of the lateral temperature gradient across the webs depends mainly on the time at which the gradient is calculated. For the mid day hours, the cantilever width has a direct impact on the degree of shading of webs and thus on the lateral temperature gradient. On the other hand, for the gradients calculated before the sunset, the sunrays have generally lower altitude at these time steps and hence there is no effect of shading, which minimizes the effect of the width of the cantilever portions.

Across the south web (section E-E), the maximum gradient occurred between 1:20 PM and 2:20 PM, therefore it is clear that the absence of cantilever slab led to higher temperature gradient as shown in Figure 7.30, while it seems that the cantilever widths beyond 1 m gave the same shading effects on the central depth of the web where section E-E is located (1.25 m below the top surface).

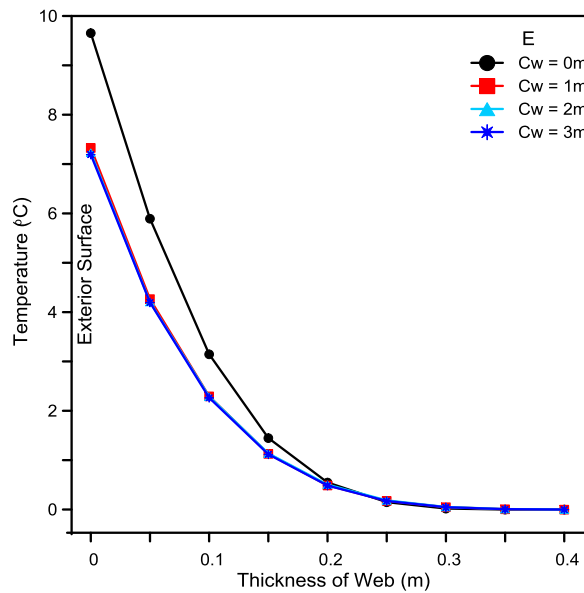


Figure 7.30 Positive temperature gradient distributions along section E-E for different cantilever widths

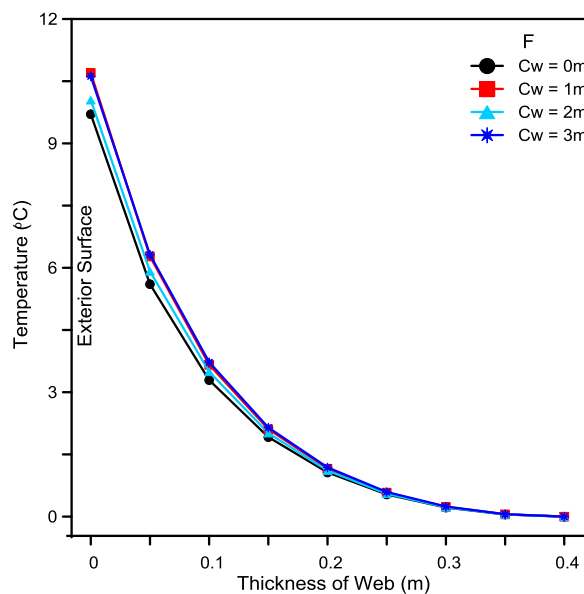


Figure 7.31 Positive temperature gradient distributions along section F-F for different cantilever widths

In June, the sun sets at the northwest direction, thus the maximum gradient across the northern web (section F-F) occurs before the sunset due to the low altitude of sunrays, which explains the minimal effect of the cantilever width of the top slab as shown in Figure 7.31.

7.5 Thickness of the Top Slab

Figures 7.32 through 7.41 show the effect of top slab thickness on the vertical and lateral temperature gradients. As shown in Figures 7.32 through 7.35, the top slab thickness within the studied range of 0.2 m to 0.5 m has no significant effect on the vertical temperature gradient value and behavior. The positive temperature gradients along the south web at the top and bottom surfaces are almost equal with maximum values of about 29°C and 7.5°C. Similar results were recorded along the north web as shown in Figure 7.34. The maximum negative vertical gradients were also almost equal along both the south and the north webs as shown in Figures 7.33 and 7.35.

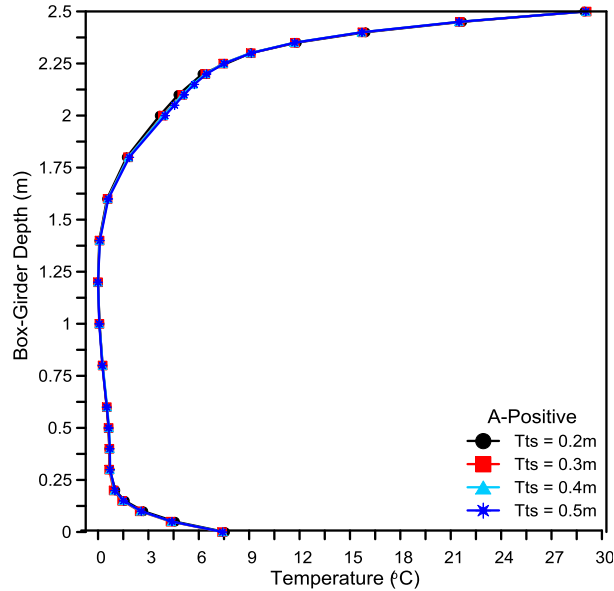


Figure 7.32 Positive temperature gradient distributions along section A-A for different thicknesses of top slab

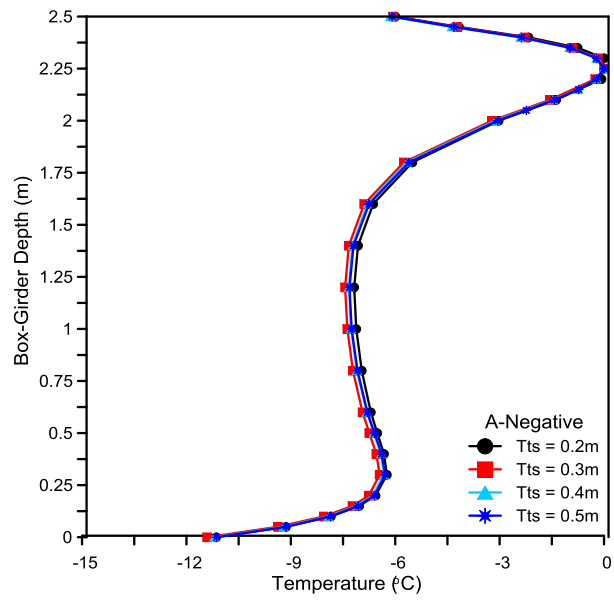


Figure 7.33 Negative temperature gradient distributions along section A-A for different thicknesses of top slab

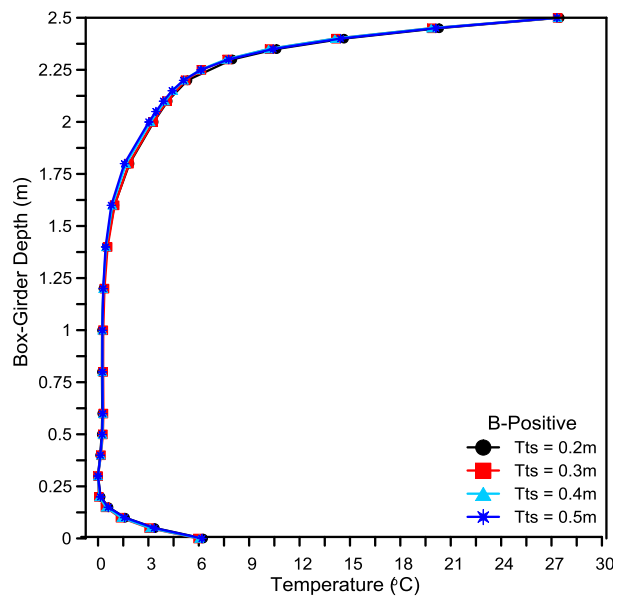


Figure 7.34 Positive temperature gradient distributions along section B-B for different thicknesses of top slab

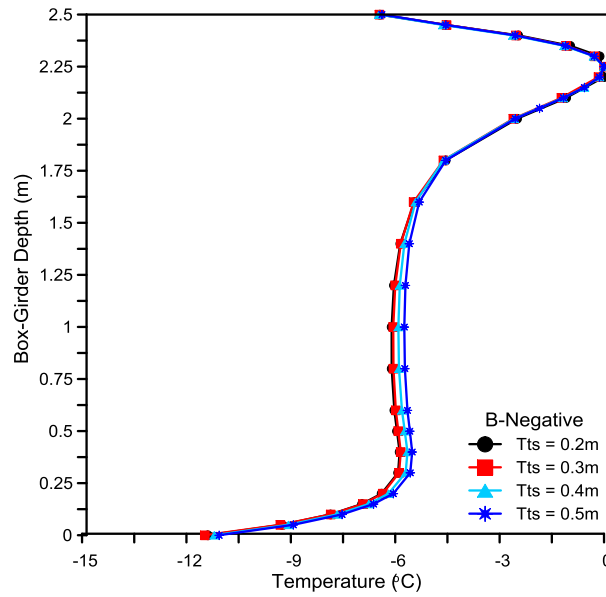


Figure 7.35 Negative temperature gradient distributions along section B-B for different thicknesses of top slab

The impact of the top slab thickness on the lateral temperature gradient along the top slab is clearly illustrated in Figure 7.36. It is known that concrete has low thermal conductivity, thus the heat gained from the top surface that exposed directly to solar radiation for long periods is the same for all groups. However, the time required for this heat to be conducted to the central depth increases as the thickness of the top slab increase. Therefore, the temperature along section C-C becomes less affected by the top surface heating and hence becomes lower as the thickness of the top slab increase as shown in Figure 7.36. The temperatures of the interior uniform gradient region along the top slab were about 6.8°C, 5.7°C, 4.6°C, and 2.8°C for top slab thicknesses of 0.2 m, 0.3 m, 0.4 m, and 0.5 m, respectively.

Due to the lower uniform gradient for the thicker slabs, their edge maximum positive lateral gradient becomes more than those of thinner thicknesses as shown in Figure 7.36. The edge maximum positive gradients were 2.3°C, 2.6°C, 6.2°C, and 6.7°C for top slab thicknesses of 0.2 m, 0.3 m, 0.4 m, and 0.5 m, respectively.

The interior uniform negative gradients along the top slab were almost equal for all slab thicknesses as shown in Figure 7.37. However, the values of the maximum negative lateral temperature gradients at both edges increased as the thickness of the

top slab decreased. The maximum negative lateral temperature gradients along section C-C at the northern edge were about 8.5°C, 8°C, 6.5°C, and 4.4°C for top slab thicknesses of 0.2 m, 0.3 m, 0.4 m, and 0.5 m, respectively, while they were about 14.3°C, 14.3°C, 12.4°C, and 10.4°C at the southern edge for top slab thicknesses of 0.2 m, 0.3 m, 0.4 m, and 0.5 m, respectively.

Figures 7.38 and 7.39 show that the thickness of the top slab has no direct effect on the lateral temperature gradients along the bottom slab (section D-D). Similarly, it has a very limited effect on the lateral gradient distributions across the webs as shown in Figures 7.40 and 7.41. The increase of the top slab thickness seems to slightly stabilize the maximum lateral gradient along the webs as shown in Figure 7.40, although this effect does not exceed 0.5°C from thickness of 0.2 m to thickness of 0.5 m.

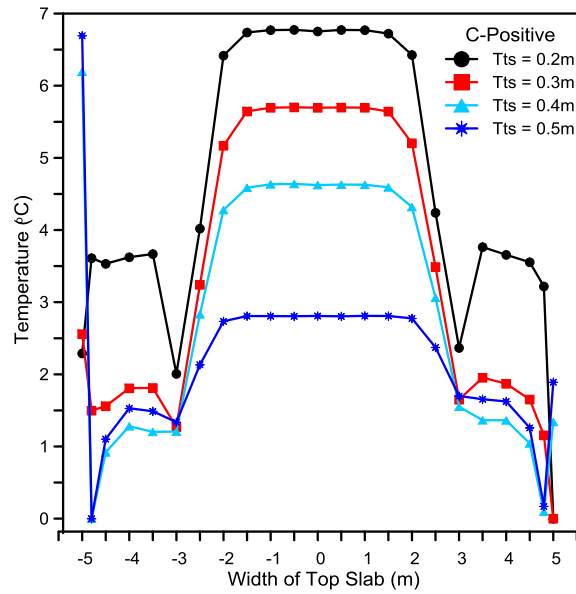


Figure 7.36 Positive temperature gradient distributions along section C-C for different thicknesses of top slab

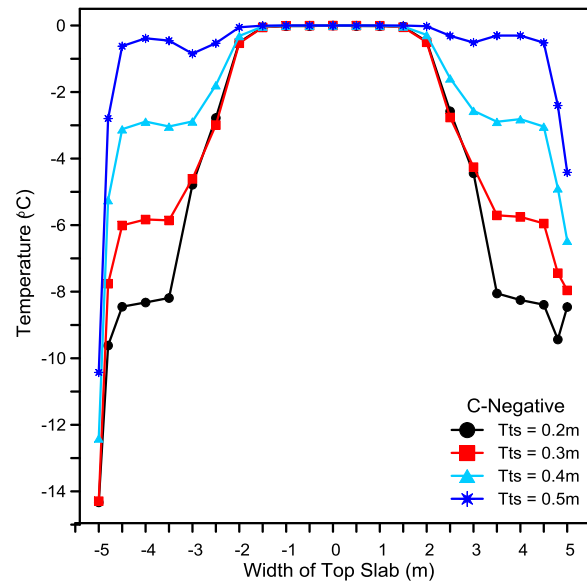


Figure 7.37 Negative temperature gradient distributions along section C-C for different thicknesses of top slab

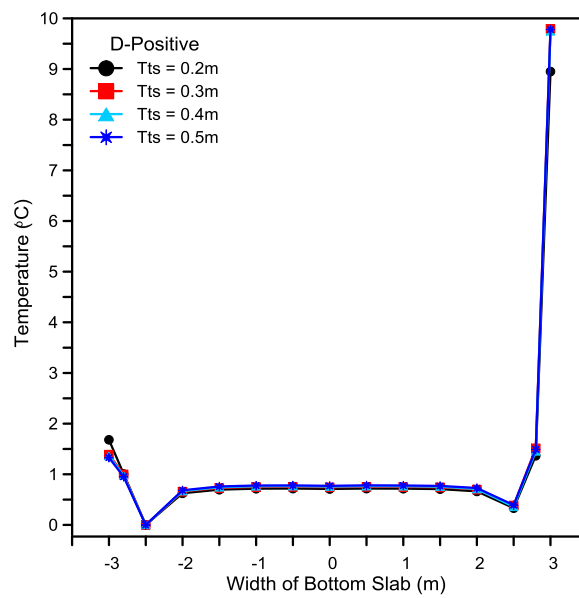


Figure 7.38 Positive temperature gradient distributions along section D-D for different thicknesses of top slab

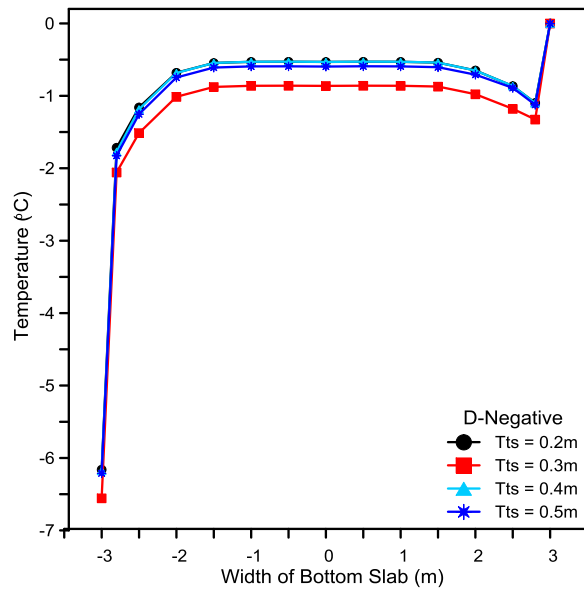


Figure 7.39 Negative temperature gradient distributions along section D-D for different thicknesses of top slab

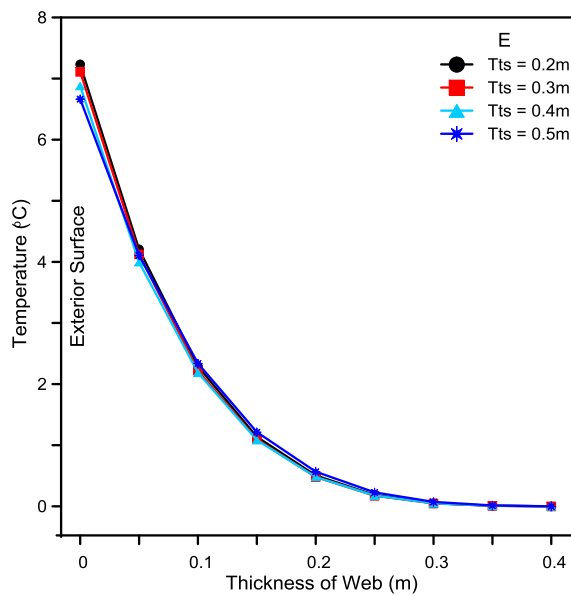


Figure 7.40 Positive temperature gradient distributions along section E-E for different thicknesses of top slab

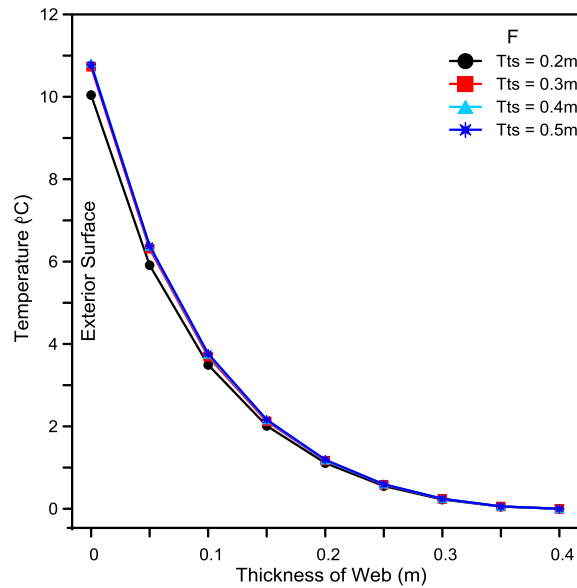


Figure 7.41 Positive temperature gradient distributions along section F-F for different thicknesses of top slab

7.6 Thickness of the Bottom Slab

It is clearly obvious from the observation of Figures 7.42 to 7.45 that the thickness of the bottom slab has no observed effect on the vertical temperature gradients along sections A-A and B-B and both for positive and negative temperature cases. The maximum positive temperature gradient was about 29°C along the south web (section A-A), while it was from 27.5°C to 27.9°C along the north web (section B-B). The maximum negative gradients were about 11.3°C and from 11.4°C to 11.6°C for sections A-A and B-B, respectively.

Similar results were observed for the lateral gradients along the top slab, where as shown in Figures 7.46 and 7.47, the maximum positive and negative lateral temperature gradients are quite the same for bottom slab thickness of 0.2 m to 0.5 m, which were about 6.8°C and -14.4°C.

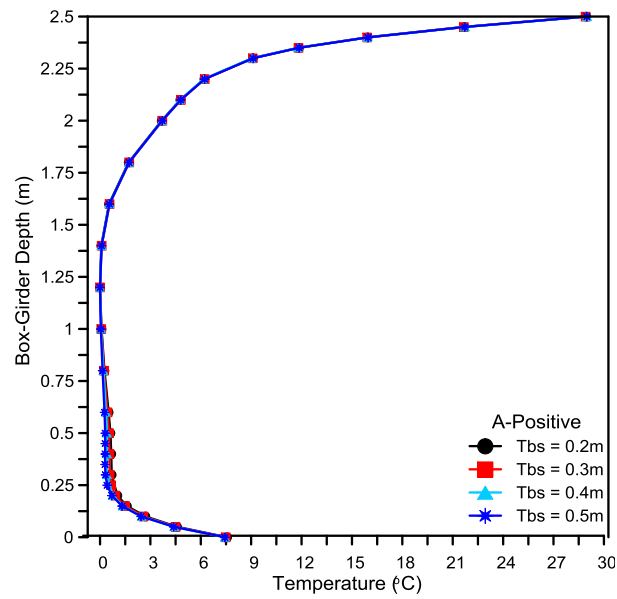


Figure 7.42 Positive temperature gradient distributions along section A-A for different thicknesses of bottom slab

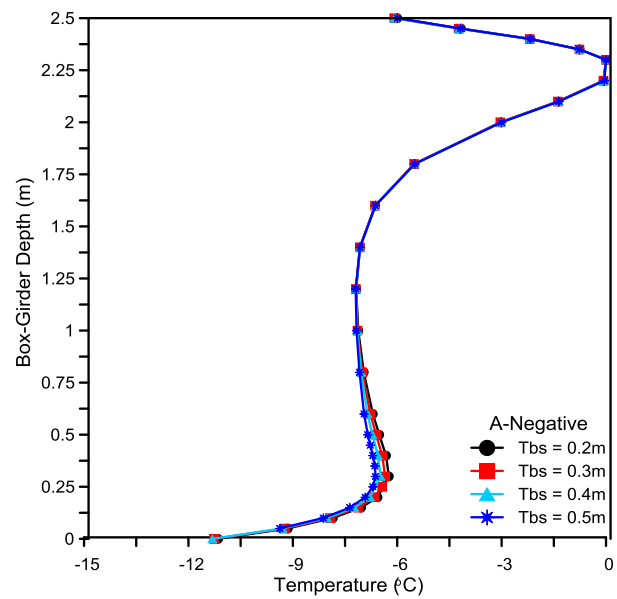


Figure 7.43 Negative temperature gradient distributions along section A-A for different thicknesses of bottom slab

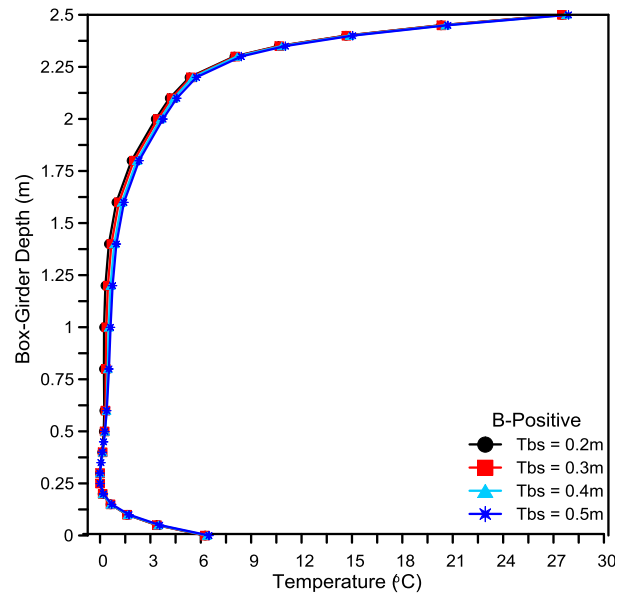


Figure 7.44 Positive temperature gradient distributions along section B-B for different thicknesses of bottom slab

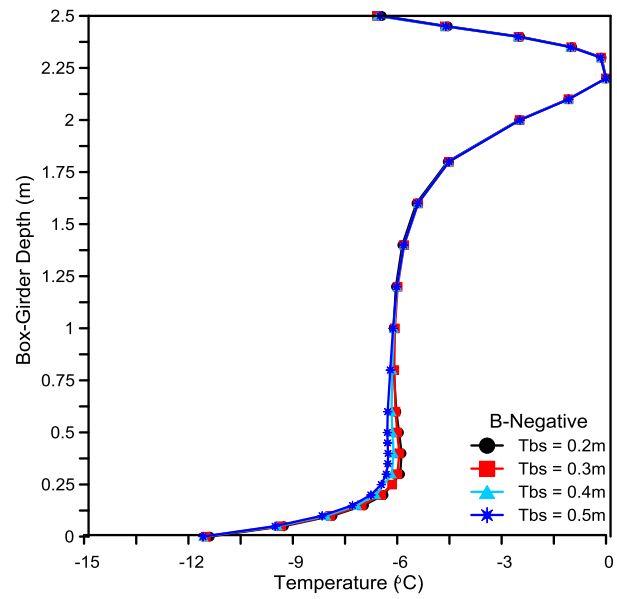


Figure 7.45 Negative temperature gradient distributions along section B-B for different thicknesses of bottom slab

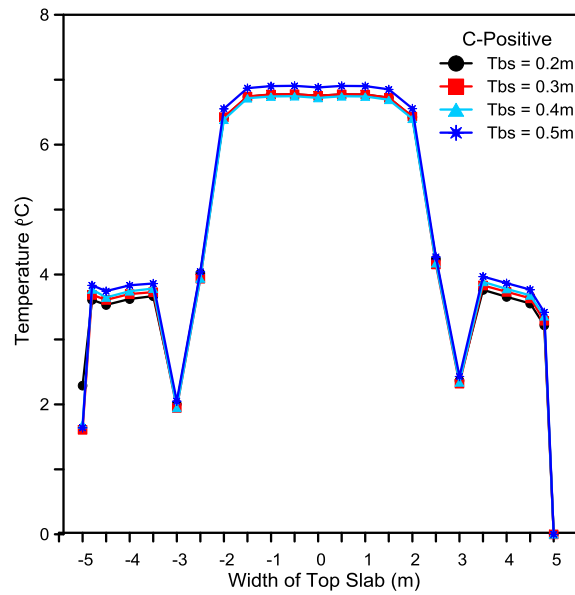


Figure 7.46 Positive temperature gradient distributions along section C-C for different thicknesses of bottom slab

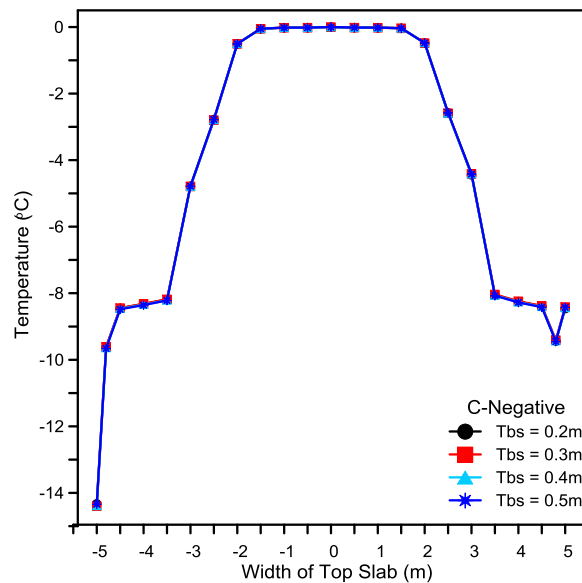


Figure 7.47 Negative temperature gradient distributions along section C-C for different thicknesses of bottom slab

The effect of the thickness of the bottom slab on the positive lateral temperature gradient along the bottom slab is shown in Figure 7.48, it is clear that the maximum positive lateral gradient increases as the thickness of the bottom slab increase. The maximum lateral temperature gradients were 9°C, 9.7°C, 10.7°C, and 12.4°C for

bottom slab thicknesses of 0.2 m, 0.3 m, 0.4 m, and 0.5 m, respectively. Thus an increase of more than 35% occurred as the thickness increased from 0.2 m to 0.5 m.

This behavior can be attributed to the low thermal conductivity of concrete compared to the rate of solar heating at the edges of the bottom slab. As the bottom slab thickness increases the heat reaches the central depth (section D-D) decrease and hence its temperature decrease leading to larger differentials from the hot edges of the slab. The uniform temperatures along the interior width of the bottom slab were about 29.3°C, 27.7°C, 26.2°C, and 24.8°C for slab thickness of 0.2 m, 0.3 m, 0.4 m, and 0.5 m, respectively, while the maximum edge temperature was from 37°C to 37.5°C for all cases.

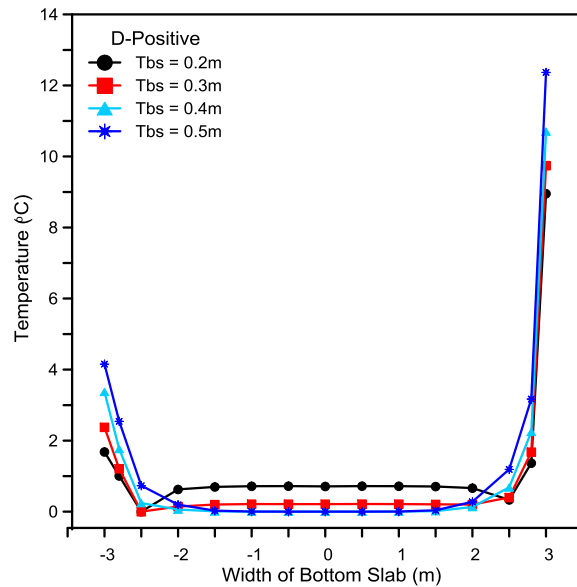


Figure 7.48 Positive temperature gradient distributions along section D-D for different thicknesses of bottom slab

For the same reason discussed above, the uniform negative gradient shown in Figure 7.49 was higher for thicker slabs. However, the maximum negative gradient was close for all cases, which ranged from -6.2°C to -6.4°C. From the observations of Figures 7.50 and 7.51 it can be concluded that the thickness of bottom slab has no significant effect on the lateral gradients across the webs.

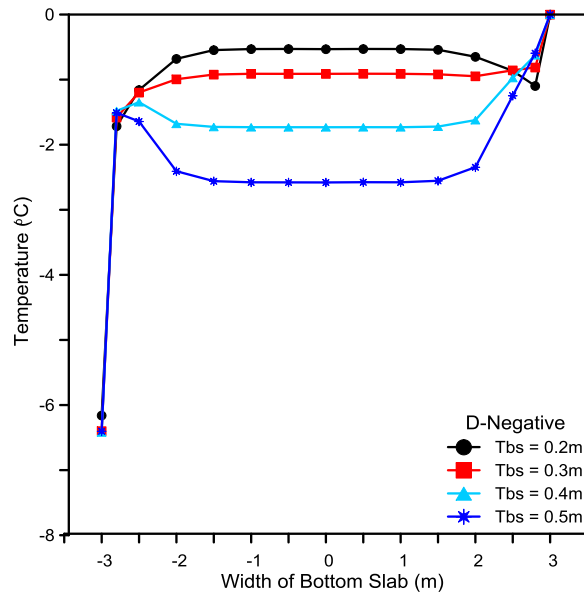


Figure 7.49 Negative temperature gradient distributions along section D-D for different thicknesses of bottom slab

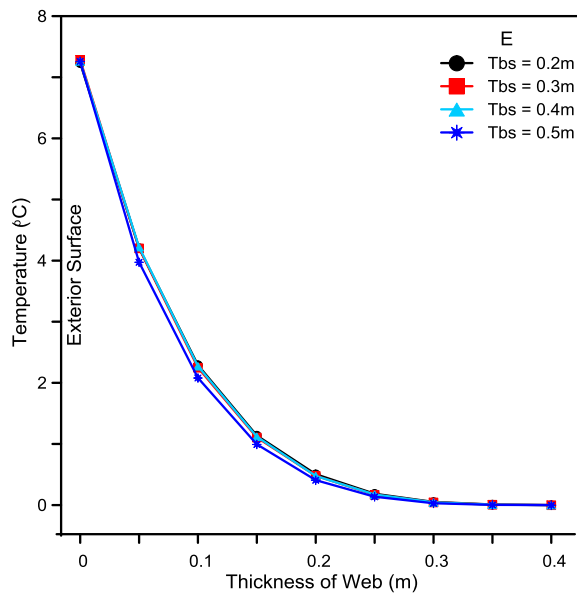


Figure 7.50 Positive temperature gradient distributions along section E-E for different thicknesses of bottom slab

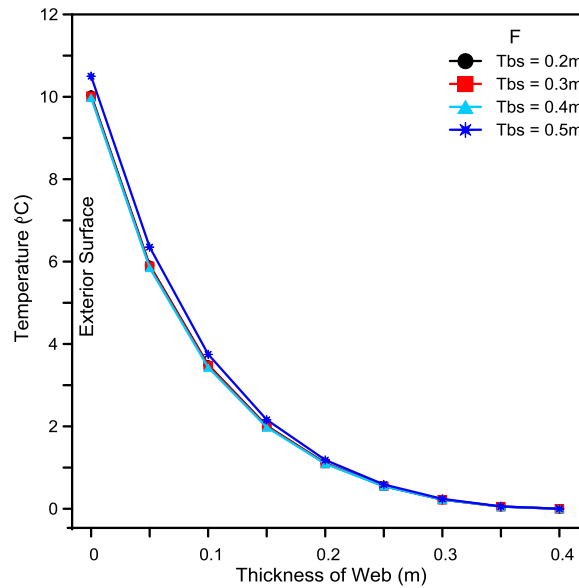


Figure 7.51 Positive temperature gradient distributions along section F-F for different thicknesses of bottom slab

7.7 Thickness of the Webs

For thin webs, the heat gained from solar radiation and temperature difference on the web surfaces increases the temperature along the centerline of the web faster than in thick webs due to the limited thermal conductivity of concrete, and as the top surface still heated at the same rate, the vertical positive temperature gradient between the top surface and the web interiors decreases along sections A-A and B-B.

It is clear in Figures 7.52 and 7.54 that the maximum positive vertical temperature gradient increases as the web thickness increase both at the top and the bottom surfaces. For section A-A, the maximum positive vertical temperature gradients were 27.4 °C, 28.1°C, 29.0°C, and 29.7°C for web thickness of 0.2 m, 0.3 m, 0.4 m, and 0.5 m, respectively. While the same sequence of maximum gradients along section B-B was 25.9 °C, 26.7°C, 27.5°C, and 28.2°C.

As shown in Figures 7.53 and 7.55, the maximum negative vertical temperature gradient decreases as the thickness of the web increase from 0.2 m to 0.5 m. As discussed above, the thinner webs conduct higher heat quantities to its centerline points and hence warm faster than thicker webs, which leads to higher interior

temperatures during the following hours where cooling from exterior surfaces takes place. Thus, the resulted negative gradients are higher for thinner webs.

The maximum interior temperatures along section A-A at the time of maximum negative gradients were 31.9°C, 31.7°C, 31.5°C, and 31.2°C for web thicknesses of 0.2 m, 0.3 m, 0.4 m, and 0.5 m, respectively. As a result, the maximum negative temperature gradients for web thicknesses of 0.2 m, 0.3 m, 0.4 m, and 0.5 m were -12.2°C, -11.7°C, -11.1°C, and -10.7°C, respectively at the bottom surface, while they were -6.3°C, -6°C, -6°C, and -5.9°C, respectively at the top surface. Similar sequence of results was recorded for section B-B as shown in Figure 7.55.

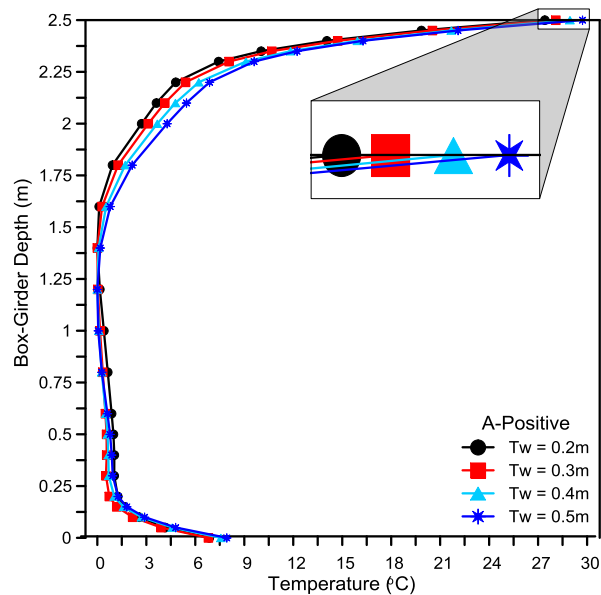


Figure 7.52 Positive temperature gradient distributions along section A-A for different web thicknesses

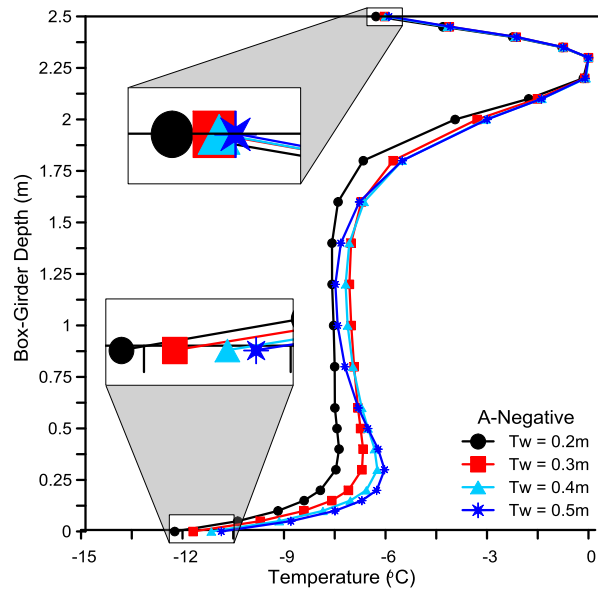


Figure 7.53 Negative temperature gradient distributions along section A-A for different web thicknesses

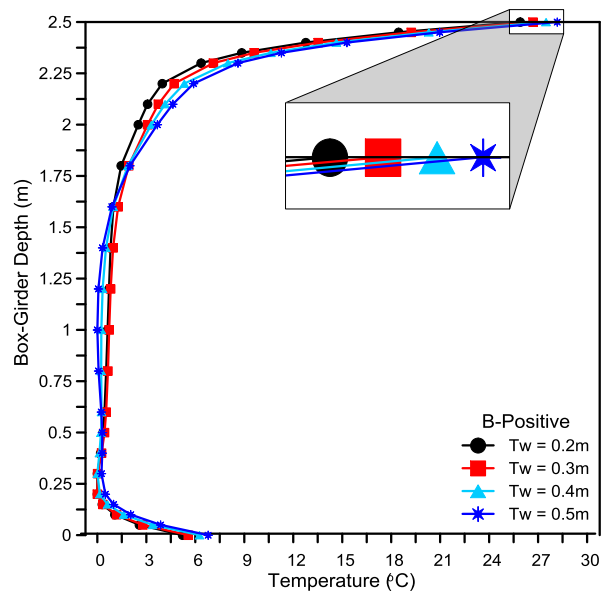


Figure 7.54 Positive temperature gradient distributions along section B-B for different web thicknesses

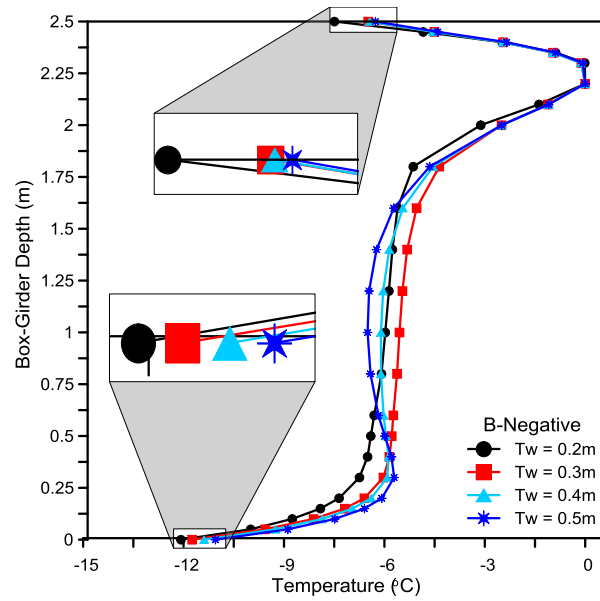


Figure 7.55 Negative temperature gradient distributions along section B-B for different web thicknesses

It is obvious from the observation of Figures 7.56 through 7.59 that there is no clear effect of web thickness on the lateral temperature gradients along the top and bottom slabs.

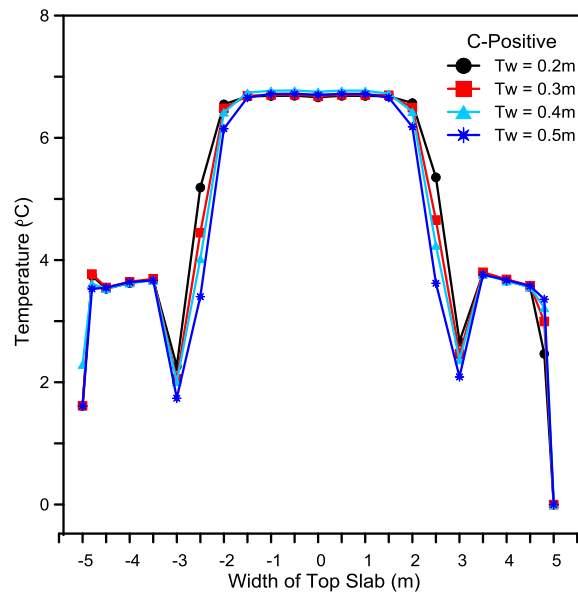


Figure 7.56 Positive temperature gradient distributions along section C-C for different web thicknesses

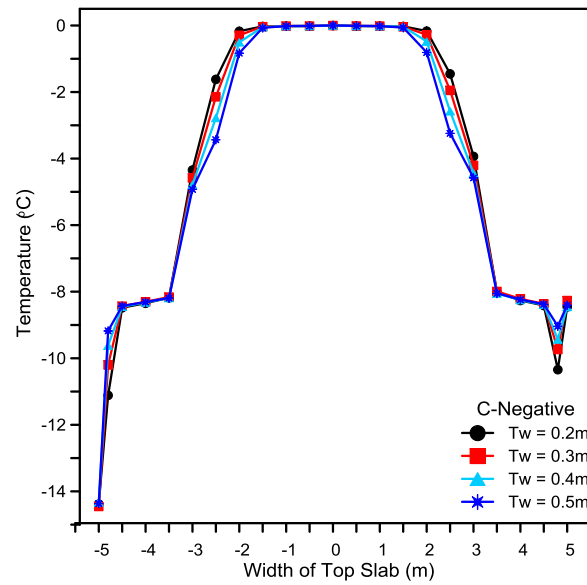


Figure 7.57 Negative temperature gradient distributions along section C-C for different web thicknesses

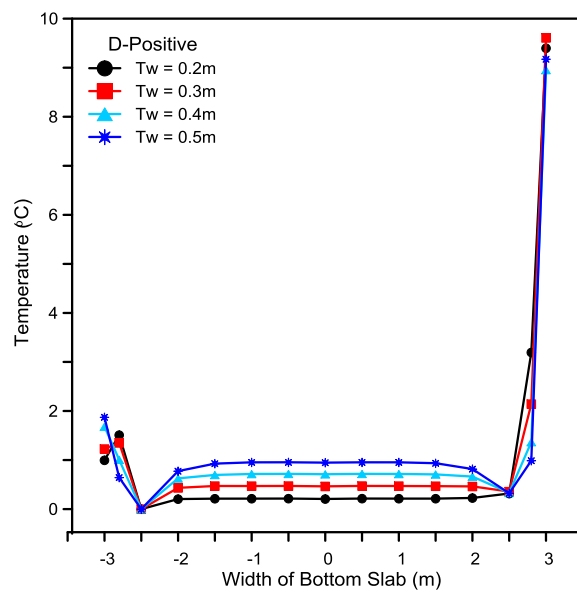


Figure 7.58 Positive temperature gradient distributions along section D-D for different web thicknesses

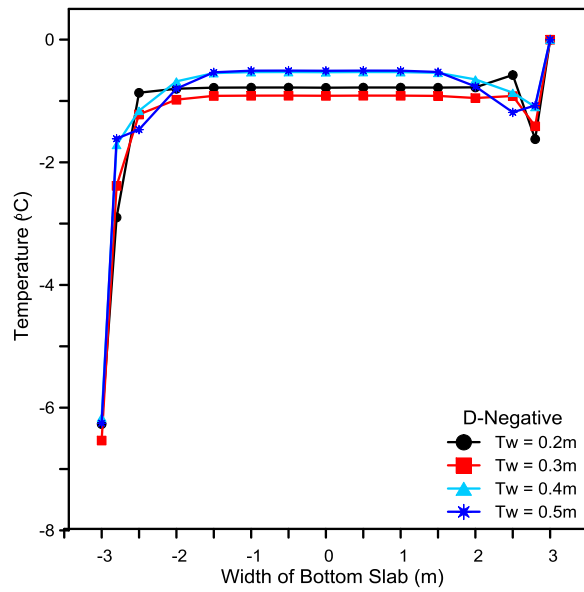


Figure 7.59 Negative temperature gradient distributions along section D-D for different web thicknesses

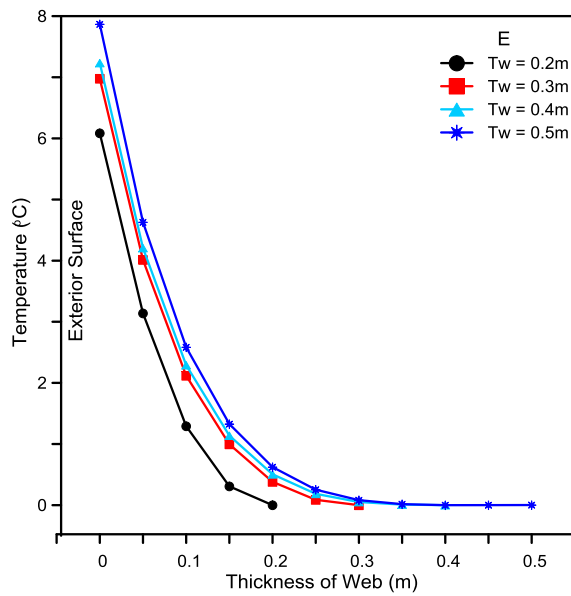


Figure 7.60 Positive temperature gradient distributions along section E-E for different web thicknesses

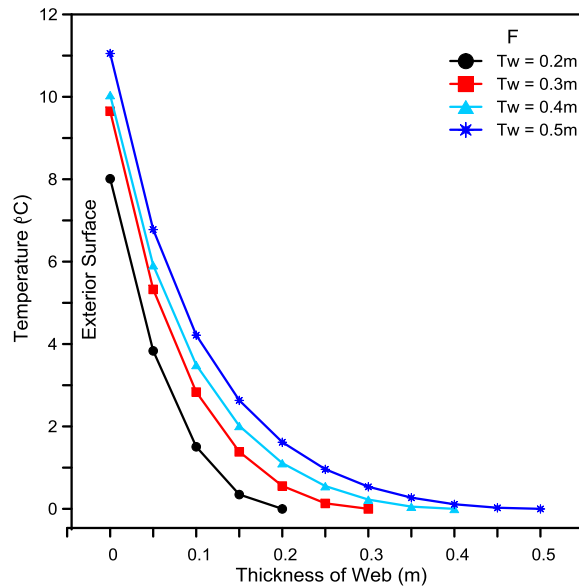


Figure 7.61 Positive temperature gradient distributions along section F-F for different web thicknesses

As shown in Figures 7.60 and 7.61, the lateral temperature gradients across the webs (sections E-E and F-F) increase as the web thickness increase. This can be attributed to the larger temperature difference occurred between the exterior heated surfaces of the webs and the interior cores or the interior surfaces inside the cavity due to the low amount of conducted heat for thicker webs due to the weak thermal conductivity of concrete. The maximum lateral temperature gradients for sections E-E and F-F for web thicknesses of 0.2 m, 0.3 m, 0.4 m, and 0.5 m were in the sequences of 6.1°C, 7°C, 7.2°C, and 7.9°C and 8°C, 9.7°C, 10°C, and 11°C, respectively.

7.8 Thickness of the Asphalt Topping Layer

In this section, the effect of the thickness of the asphalt topping layer is presented and discussed. The asphalt topping layer is assumed to has an equal emissivity and absorption coefficients of 0.9. The density, the thermal conductivity, and the specific heat were considered as 2100 kg/m^3 , $1.0 \text{ W/m}^\circ\text{C}$, and $920 \text{ J/kg}^\circ\text{C}$.

As shown in Figure 7.62, the asphalt topping layer has a significant effect on the vertical positive temperature gradient along the web. The topping with a 50 mm of asphalt increased the temperature of the top surface of the slab from about 53°C to

about 59°C. This is because of the high solar absorptivity of asphalt compared to concrete, which leads to higher amount of absorbed heat. Thus, due to the low thickness of the asphalt layer (only 50 *mm*), a higher amount of heat is conducted to the top surface of the concrete box-girder, which in turn raises the temperature of this surface. However, thicker layers of asphalt led to lower temperature of the top surface of concrete and to significant delays in the time of maximum temperature gradient. As the thickness of the topping layer increases, the heat needs much time to be conducted, also the thicker layers keep higher amounts of heat within the layer itself, which reduces the total amount of the heat conducted to the top concrete surface and hence reduces its temperature and temperature gradient.

The temperatures of the top surface of the box girder along the south web (section A-A) for asphalt layer thicknesses of 0 *m*, 0.05 *m*, 0.1 *m*, 0.15 *m*, and 0.2 *m* were 53.6°C, 59.3°C, 51.4°C, 45.6°C, and 41.6°C, respectively. While the corresponding vertical temperature gradients were about 29°C, 34.4°C, 25.9°C, 20°C, and 15.8°C, respectively. Similar results with similar sequences can be noticed for the north web along section B-B as shown in Figure 7.64.

The maximum vertical negative gradient distribution in summer showed different results for the top and bottom surfaces as shown in Figures 7.63 and 7.65. The maximum negative gradient at the top surface decreased as the thickness of the asphalt layer increased because the heat conduction from the hot asphalt layer continues during the night hours, and as the thickness of the asphalt layer increases the amount of the conducted heat increase during this period, which results in higher top surface temperatures for the thicker asphalt layers.

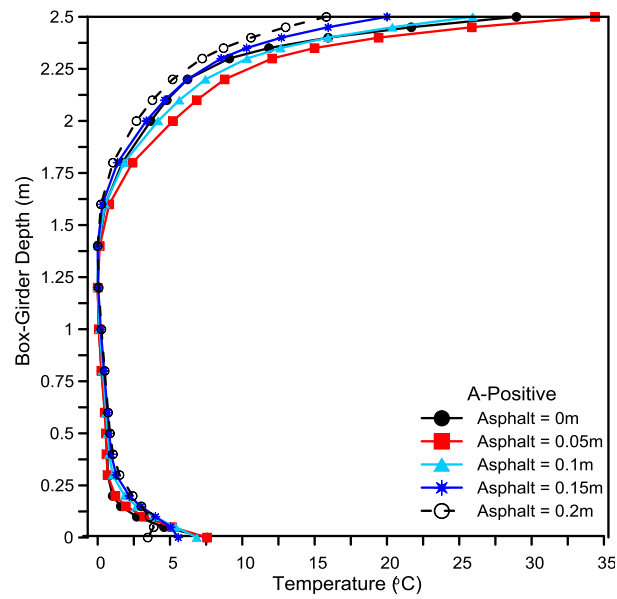


Figure 7.62 Positive temperature gradient distributions along section A-A for different thicknesses of asphalt topping layer

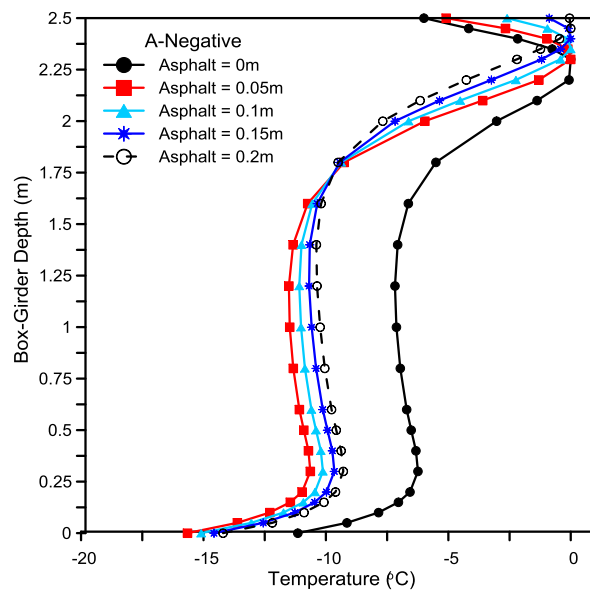


Figure 7.63 Negative temperature gradient distributions along section A-A for different thicknesses of asphalt topping layer

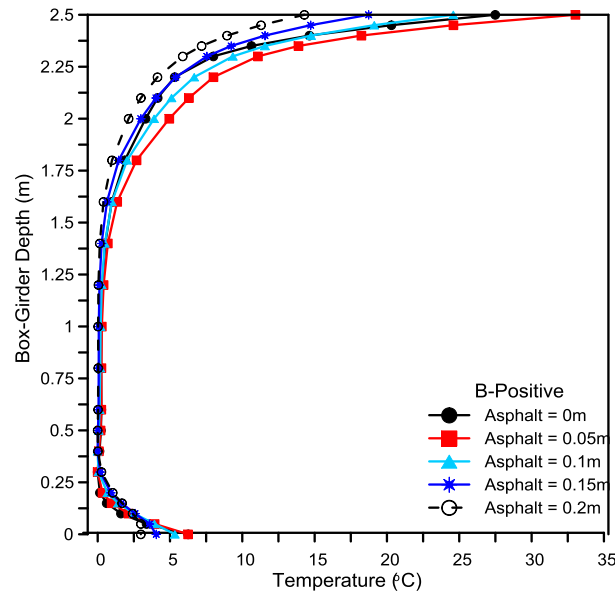


Figure 7.64 Positive temperature gradient distributions along section B-B for different thicknesses of asphalt topping layer

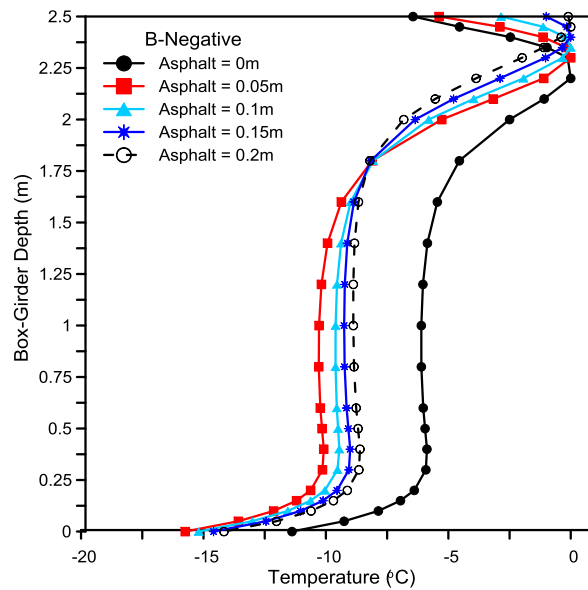


Figure 7.65 Negative temperature gradient distributions along section B-B for different thicknesses of asphalt topping layer

It is clear in Figure 7.66 that as discussed for the positive vertical temperature gradients along the box-girder depth, the uniform temperature along the mid-width of the top slab during the midday hours is higher for shallower asphalt thicknesses and decreases as the thickness of the layer increase, which results in the temperature

gradient distribution shown in Figure 7.66. The maximum positive lateral temperature gradients along the top slab for asphalt layer thicknesses of 0 m, 0.05 m, 0.1 m, 0.15 m, and 0.2 m were 6.8°C, 12.5°C, 11.2°C, 8.9°C, and 7.4°C, respectively.

The lateral negative gradient distributions along the top slab are shown in Figure 7.67, in which it is clear that the maximum negative lateral temperature gradient almost follows the similar sequence that discussed above for positive gradient. However, the maximum gradients occurred at the slab's edge rather than at its center. The maximum negative lateral temperature gradients along the top slab for asphalt layer thicknesses of 0 m, 0.05 m, 0.1 m, 0.15 m, and 0.2 m were -14.3°C, -22.2°C, -22.3°C, -21.1°C, and -19.3°C, respectively.

Because of the location of the asphalt layer compared to the bottom slab and the mid-thickness sections of the webs (section D-D, and sections E-E and F-F), the thickness of the topping layer has no any noticeable effect on the lateral temperature gradients along the bottom slab and across the webs as shown in Figures 7.68 to 7.71.

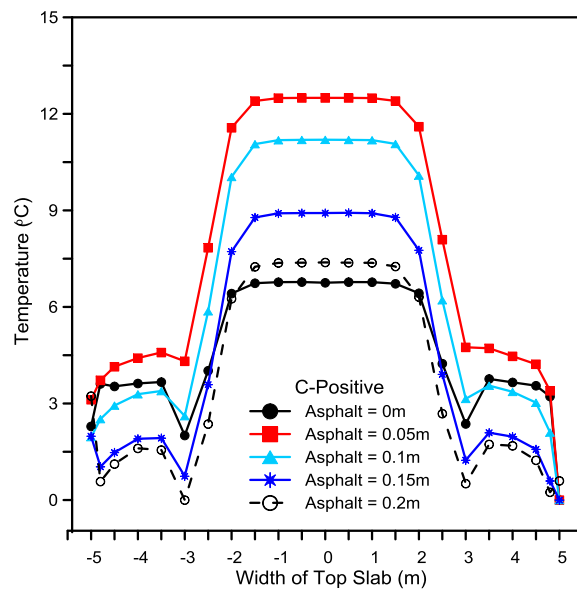


Figure 7.66 Positive temperature gradient distributions along section C-C for different thicknesses of asphalt topping layer

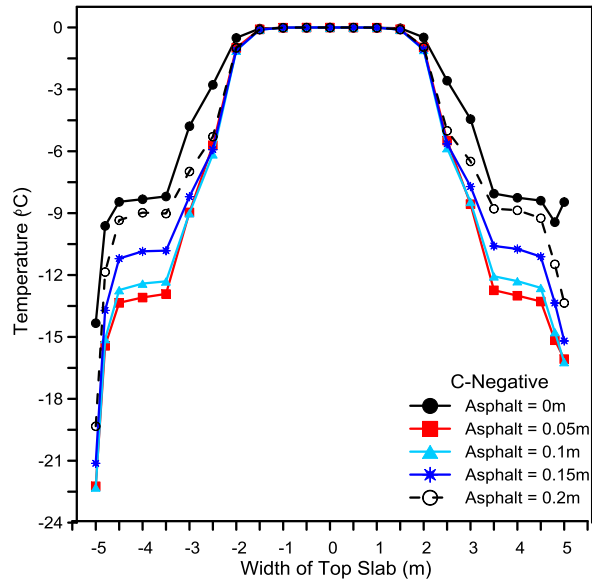


Figure 7.67 Negative temperature gradient distributions along section C-C for different thicknesses of asphalt topping layer

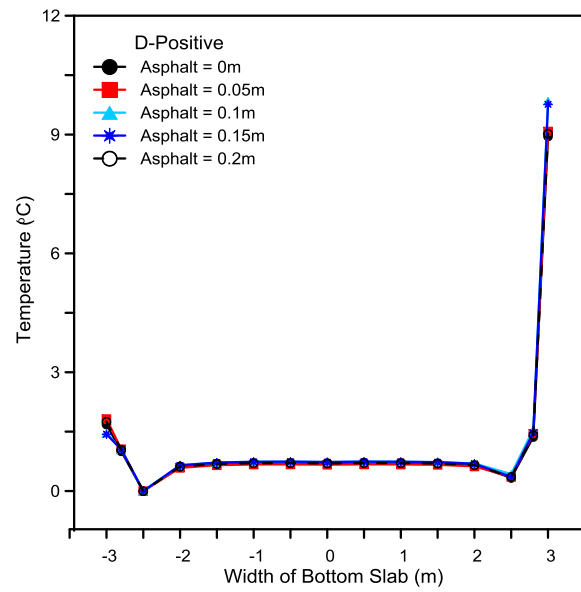


Figure 7.68 Positive temperature gradient distributions along section D-D for different thicknesses of asphalt topping layer

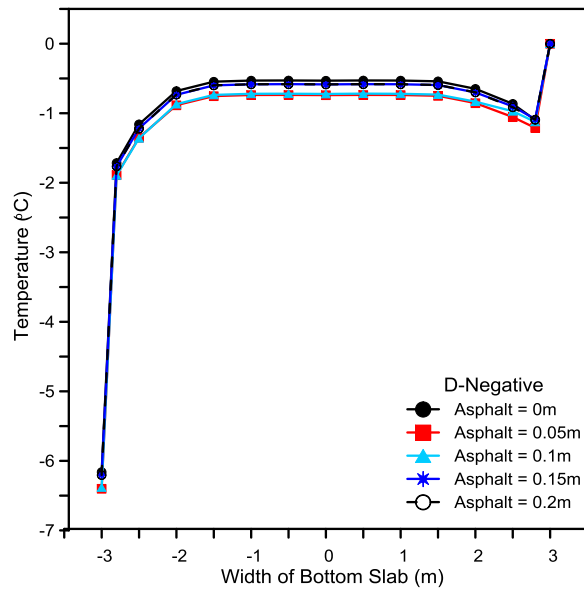


Figure 7.69 Negative temperature gradient distributions along section D-D for different thicknesses of asphalt topping layer

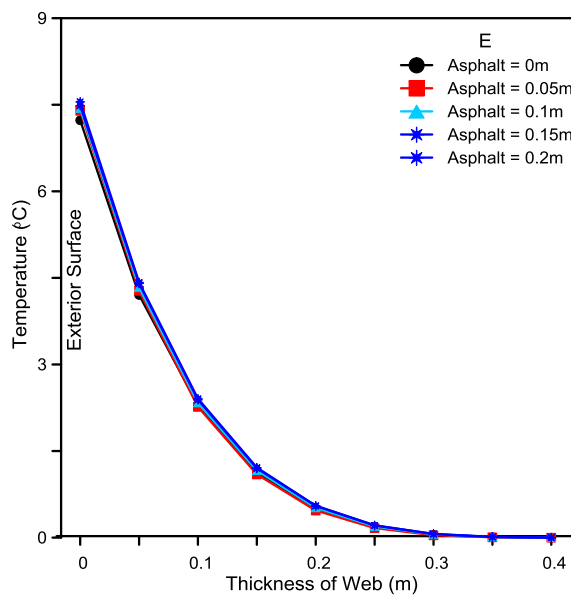


Figure 7.70 Positive temperature gradient distributions along section E-E for different thicknesses of asphalt topping layer

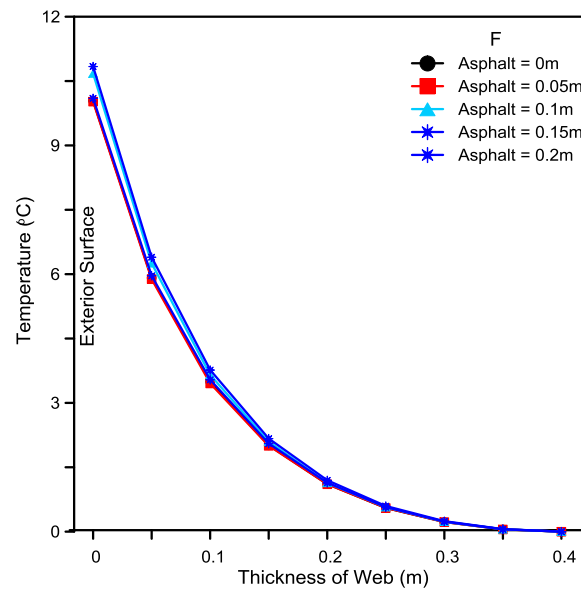


Figure 7.71 Positive temperature gradient distributions along section F-F for different thicknesses of asphalt topping layer

CHAPTER EIGHT

THERMAL PROPERTIES OF CONCRETE

8.1 General

In this chapter, the effect of concrete thermal properties on temperature distributions in concrete girders is discussed in details. Because concrete is a composite material, the thermal behavior of concrete bridges is affected by the variation of the properties of the concrete constituents. As shown in Equation 6.1, which controls the heat transfer in solid members, three material properties are included in the equation, namely are the density ρ , the specific heat C_p , and the thermal conductivity k . These three material properties together are referred to as the thermal diffusivity $k/\rho C_p$. Moreover, two surface material properties have also a significant influence on the heating and cooling processes on the boundaries, these are the absorptivity and the emissivity. A wide literature review was used as a primary identification tool to estimate the possible range of change of the mentioned five material properties to investigate their effects on the temperature distributions and variations in concrete girders. Tables 8.1 to 8.4 include the values and ranges of the studied material properties of concrete as found in the literature [21, 26, 74-89].

8.2 The Ranges of the Thermal Properties

8.2.1 Concrete Density

Because concrete aggregates differ from light to normal weight, its density has a wide range of variation. However, in bridge construction, the used concrete is mostly normal weight. Therefore, a density range of 2200 to 2400 kg/m^3 is quite reasonable for purpose of the current parametric study. Based on the literature concerned with the thermal properties of concrete, Table 3.1 shows some values of concrete density of normal weight aggregate concretes.

8.2.2 Thermal Conductivity

Thermal conductivity of concrete depends mainly on the type of aggregate and the moisture content. Based on the composition and the moisture condition, detailed tables for thermal conductivity ranges were introduced in some references, while other references suggested overall ranged values. ACI 122R-02 [74] introduced the thermal conductivity of concrete as an exponential relationship with concrete density as shown in Table 8.1. Experimental tests performed by VanGreem [90] on high strength concrete showed that the values of thermal conductivity of high strength concrete are similar to that of normal strength concrete. Table 8.1 shows the values of thermal conductivity of concrete as found in the extant literature, while Table 8.2 and Table 8.3 show values of thermal conductivity of concrete for different types of aggregates and different moisture states. As listed in Tables 8.1 to 8.3, the values of thermal conductivity of normal weight concrete varies from 1.0 to 3.6 $W/m K$.

Table 8.1 Values of concrete density and thermal conductivity

Reference	Density kg/m^3	Thermal Conductivity $W/m K$
ACI 122R-02 [74]		For concrete walls $k_c = 0.0865e^{0.00125 d}$
Adrian Bejan [75]	2200	1.28
ASHRAE fundamental Handbook 2001[76]	2400	1.4-2.9
	2240	1.3-2.6
	2080	1.0-1.9
Duffie and Beckman [77]	2400	1.73
Ghali et al. [26]	2400	1.5-2.5
Incropera et al. [78]	2300	1.4
Kothandaraman [79]	2300	1.279
Naterer [80]	2200	1.7
Neville [21]		1.4-3.6
Porges [81]	2240	1.2-1.4
Ramachandran [82]		1.55-2.17
Turns and Kraige [83]	2300	1.4
Welty et al. [84]	2310	1.21

It was found that extreme thermal conductivity values such as 1.0 and 3.6 $W/m K$ are listed in the literature, however, values as low as 1.0 $W/m K$ and as high as 3.6 $W/m K$ are not common in the studies of thermal analysis of bridges. Many studies concerning with the thermal analysis of different types of bridge were reviewed. In these studies, thermal conductivity commonly ranges between 1.3 and 2.5 $W/m K$.

Table 8.2 Values of concrete density and thermal conductivity based on the type of aggregate

Reference	Density kg/m^3	Thermal Conductivity W/m K					
Tatro [85]	2.24-2.4		Limestone		Sandstone		Quartz Gravel
		Moist	2.2		2.9		3.3
		50% RH	1.7		2.2		2.7
		Dry	1.4		1.4		2.3
Mehta and Monteiro [86]		Basalt	Rhyolite	Granite	Limestone	Dolomite	Quartzite
		1.9-2.2	2.2	2.6-2.7	2.6-3.3	3.2	3.5

Table 8.3 Values of concrete density and thermal conductivity based on the moisture content of concrete

Reference	Density kg/m^3	Thermal Conductivity W/m K	
Somerton [87]	2100	Dray	Saturated
		1.33-1.63	2.54-2.87

8.2.3 Specific Heat

Specific heat refers to the amount of heat that is required to raise the temperature of a unit mass by one degree. The range of specific heat of concrete that was found in the reviewed literature is 753 to 1200 J/kg K as shown in Table 8.4. However, values lower than 800 J/kg K are rare in bridge analysis studies.

8.2.4 Surface Absorptivity and Emissivity

Concrete solar absorptivity, which refers to the fraction of solar radiation absorbed by the surface, ranges from 0.5 to 0.8 based on the surface color and condition. Emissivity is the surface property indicating the radiation of the surface compared to the ideal black body radiation. As listed in Table 8.4, concrete emissivity values vary from 0.85 to 0.95. For solar absorptivity on the other hand, values in the range of 0.5 to 0.7 are mostly used in the thermal analysis of concrete bridges.

Table 8.4 Values of concrete specific heat, surface emissivity, and surface absorptivity

Reference	Specific Heat $J/kg\ K$	Emissivity	Absorptivity
ACI 122R-02 [74]	880-920		
Adrian Bejan [75]	880		
ASHRAE fundamental Handbook 2001 [76]	800-1000	0.85-0.95	0.65-0.8
Duffie and Beckman [77]	840		
Ghali et al. [26]	840-1200	0.9	0.65-0.8
Incropera et al. [78]	880	0.88-0.93	
Kothandaraman [79]	1130		
Naterer [80]	753	0.85-0.95	0.5
Neville [21]	840-1170		
Porges [81]	1130		
Turns and Kraige [83]	880	0.88-0.93	
Welty et al. [84]	880		
Tatro [85]	917-1038		
Mehta and Monteiro [86]	900-1000		
ASHRAE fundamental Handbook 2009 [88] Rough concrete surface		0.91	0.6
CIBSE Guide C: Reference Data [89]		0.85-0.95	0.65-0.8

8.3 The Analysis of Variance (ANOVA)

One way ANOVA is a statistical tool used for the comparison between the means of three or more data groups that share one dependent variable. One way ANOVA calculates for the Sum of Squares (SS), the Degree of Freedom (DF), and the Mean Square (MS) for each data group (within group) and for all groups of data (between groups).

ANOVA then uses the F-test to accept or reject the null hypothesis at a stated level of significant. The F-test is the ratio of the between-groups MS to the within-groups MS. The null hypothesis assumes that there are no differences between the means of the tested groups. If there are serious differences between the means of the tested groups, the null hypothesis will be rejected by the F-test showing high values of F-factor and low P-values at the tail of the F-distribution.

ANOVA is usually used as a primary estimation tool to evaluate the degree of influence of the studied parameters on the test. ANOVA can be used with

quantitative or qualitative data. The function of analysis of variance is to find whether each input has a significant effect on the system's response. Thus, ANOVA is often used at an early stage in the analysis of quantitative data [91].

8.3.1 The Parametric Studies for ANOVA

To investigate the effect of the concrete thermal properties on temperature distributions in concrete box-girder bridges, five different parametric studies were conducted. In the thermal analysis of the parametric studies, the air temperature, solar radiation, wind speed, and albedo of the 10-July-2013 were used. In each parametric study, one material property was varied, while the other material properties were constant.

Concrete density was the variable of the first study, in which concrete density was in the range of 2200 to 2400 kg/m^3 with a variation step of 100 kg/m^3 . In the second study, thermal conductivity was the studied parameter. The investigated values of thermal conductivity were 1.3, 1.6, 1.9, 2.1, and 2.5 $W/m K$. In the third parametric study, the concrete specific heat was the variable parameter with variable values of 800, 900, 1000, 1100, and 1200 $J/kg K$. Solar absorptivity was the fourth studied parameter with investigated values of 0.5, 0.55, 0.6, 0.65, and 0.7. Finally, in the fifth parametric study, the surface emissivity was the variable parameter with values of 0.85, 0.9, and 0.95, respectively.

The results from the five individual parametric studies were used to analyze the particular influence of each parameter on the temperature distributions in the box-girder. In this chapter, one-way ANOVA studies were conducted at a 0.05 level of significance. This means that P-values less than 0.05 refer to significant variances between the investigated groups. Thus, the investigated parameter, which is the material property, has a significant effect on the test under investigation.

8.3.2 The Results of the One-Way ANOVA

The resulted F and P values from the one-way ANOVA studies for the five studied concrete material properties are summarized in Tables 8.5 and 8.6. The thermocouple daily temperature differences at the southern web, the northern web,

the top slab, and the bottom slabs were used as testing tools in the one-way ANOVA as listed Table 8.5. Furthermore and as shown in Table 8.6, the hourly average bridge temperature and the hourly maximum bridge temperature were also used as testing tools in the current one-way ANOVA analysis.

The one-way ANOVA studies disclosed that the density and the surface emissivity of concrete have negligible effects on the studied temperature distributions. The P-values of the six conducted tests were higher than 0.05. On the other hand, the specific heat, the thermal conductivity, and the solar absorptivity showed significance in some of the six tests and insignificance in others as listed in Table 8.5 and Table 8.6. Depending on the results of the one way ANOVA, the density and surface emissivity of concrete were considered to have negligible effects and hence were omitted from the subsequent detailed studies. On the contrary, the specific heat, the thermal conductivity, and the solar absorptivity were considered effective and are discussed in more details in the following sections.

Table 8.5 Results summary of the one-way ANOVA based on thermocouple groups daily temperature difference.

Temperature Test °C	Density ρ		Specific Heat C_p		Conductivity k		Absorptivity a		Emissivity ϵ	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
SW	0.14	0.867	2.5	0.085	0.62	0.541	0.89	0.411	0.02	0.983
NW	0.21	0.812	3.51	0.032	1.38	0.254	1.62	0.201	0.04	0.965
TF	2.29	0.105	43.12	0.000	10.47	0.000	28.54	0.000	1.27	0.285
BF	0.53	0.59	8.97	0.000	1.89	0.156	3.14	0.047	0.02	0.984

Table 8.6 Results summary of the one-way ANOVA based on the hourly average and maximum bridge temperatures

Temperature Test °C	Density ρ		Specific Heat C_p		Conductivity k		Absorptivity a		Emissivity ϵ	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Hourly Average Bridge Temperature	0.01	0.991	0.01	0.991	0.00	0.998	5.92	0.004	0.07	0.931
Hourly Maximum Bridge Temperature	0.00	0.998	0.00	1.0	0.45	0.641	6.82	0.002	0.24	0.787

8.4 The Parametric Studies of the Material Thermal Properties

Depending on the conducted ANOVA studies, the specific heat, the thermal conductivity, and the solar absorptivity of concrete were found to be effective on temperature distributions in concrete box-girders, while the concrete density and the surface emissivity were found to be of negligible effects. The temperature distributions at two time steps were elected to visualize the effect of the studied parameters. These are the temperature distributions at the early morning (at 5:00 AM or 6:00 AM) and the temperature distributions at 3:00 PM. The temperature distribution at 3:00 PM was selected because the maximum bridge temperature and the maximum vertical temperature difference occur near this time step.

To show the reality of the results and to make it easy to follow the discussion, figures for the two time steps are visualized, while the results of only the temperature distributions at 3:00 PM are discussed in details.

8.4.1 The Individual Parametric Studies of Thermal Properties

Figures 8.1 to 8.8 show the results of the parametric study of thermal conductivity, while Figures 8.9 to 8.16 and Figures 8.17 to 8.24 present the temperature results of the parametric studies of the specific heat and the solar absorptivity, respectively.

As shown in Figures 8.1 to 8.24, four temperature distributions were used to present the effect of the studied parameters. These temperature distributions are:

- a. Across the 200 *mm* thickness of the top slab along the south web (SW top 200 *mm*).
- b. Across the 250 *mm* thickness of the south web at the mid height (SW Mid Height).
- c. Along the full 7.25 *m* width of the top slab (TS).
- d. Along the full 4.75 *m* width of the bottom slab (BS).

8.4.1.1 Thermal Conductivity

The results of the top 200 *mm* of the south web (SW top 200 *mm*) show a maximum percentage temperature difference of about 0.9%, 2%, 3.3%, and 4.9% as

thermal conductivity decreases from 2.5 to 2.2, 1.9, 1.6, and 1.3 $W/m K$, respectively. As shown in Figure 8.2, the maximum differences in temperature at 3:00 PM occur at the exterior top surface.

The temperature distributions across the thickness of the south web (Figure 8.4) showed lower influence of the decrease of the thermal conductivity value. A maximum temperature increase of about 2% occurred at the outer surface of the web as thermal conductivity changed from 2.5 to 1.3 $W/m K$.

The top slab (TS) temperature distributions shown in Figure 8.8 exhibited temperature differences of about 0.7%, 1.5%, 2.4%, and 3.8% for thermal conductivities of 2.2, 1.9, 1.6, and 1.3 $W/m K$ compared to the 2.5 $W/m K$ thermal conductivity.

The bottom slab (BS) showed similar sequence as TS but with lower percentage differences as shown in Figure 8.6. It should be addressed here, that TS and BS temperature distributions showed higher percentage differences in the morning than in the afternoon, where at 6:00 AM, TS exhibited a maximum percentage of difference of 7.8% compared to the 3.8% shown at 3:00 PM as shown in Figure 8.7.

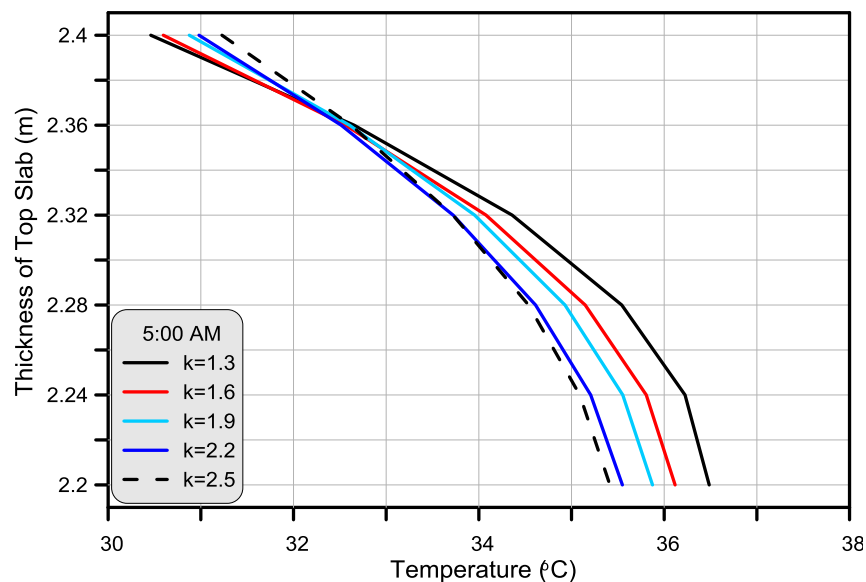


Figure 8.1 Thermal conductivity parametric study: temperature distributions along the SW top 200 mm at 5:00 AM

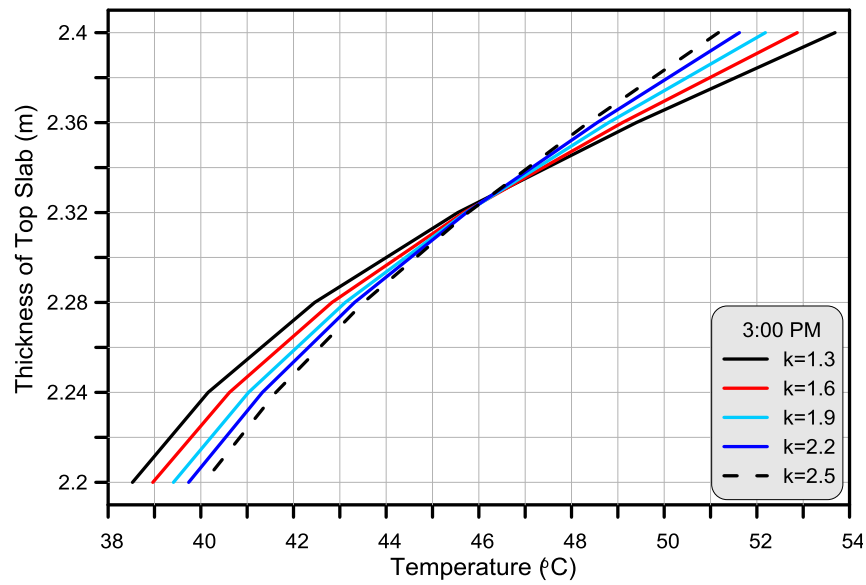


Figure 8.2 Thermal conductivity parametric study: temperature distributions along the SW top 200 *mm* at 3:00 PM

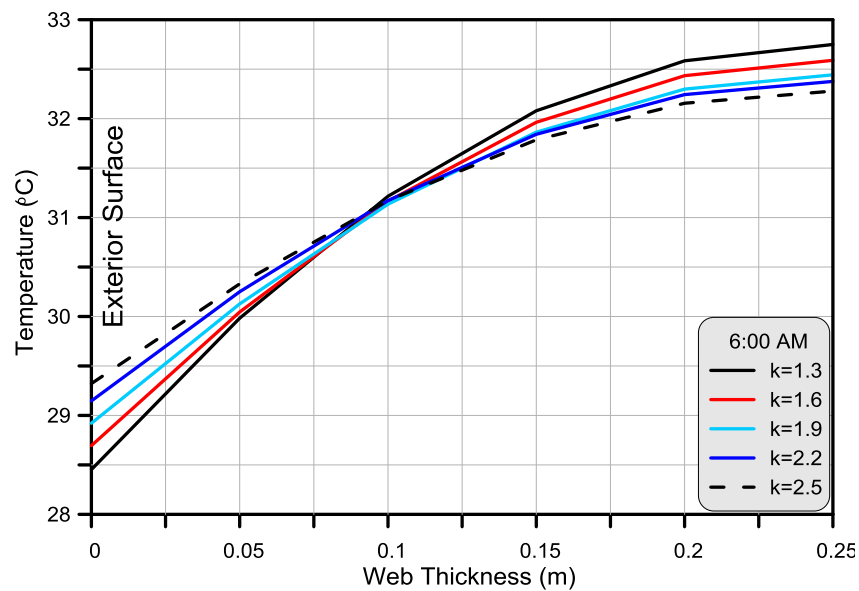


Figure 8.3 Thermal conductivity parametric study: temperature distributions across the web at 6:00 AM

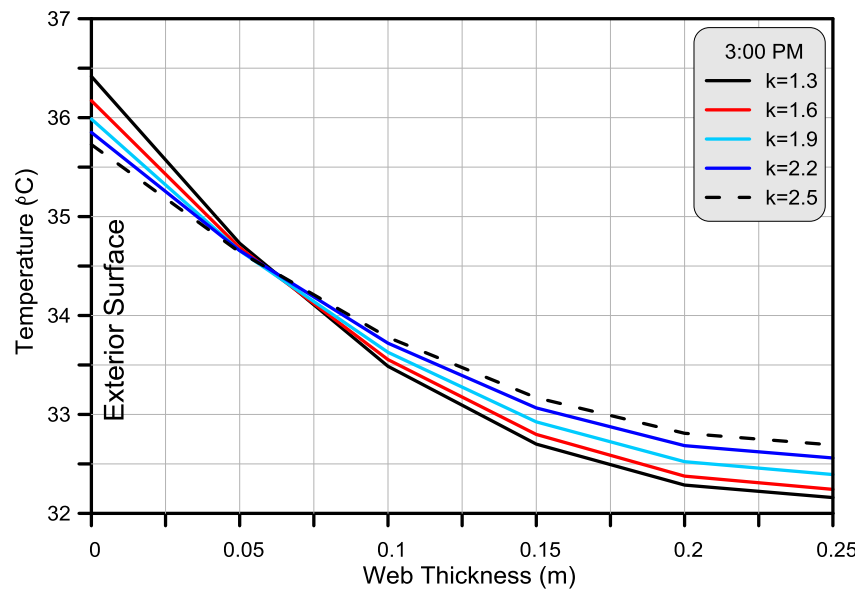


Figure 8.4 Thermal conductivity parametric study: temperature distributions across the web at 3:00 PM

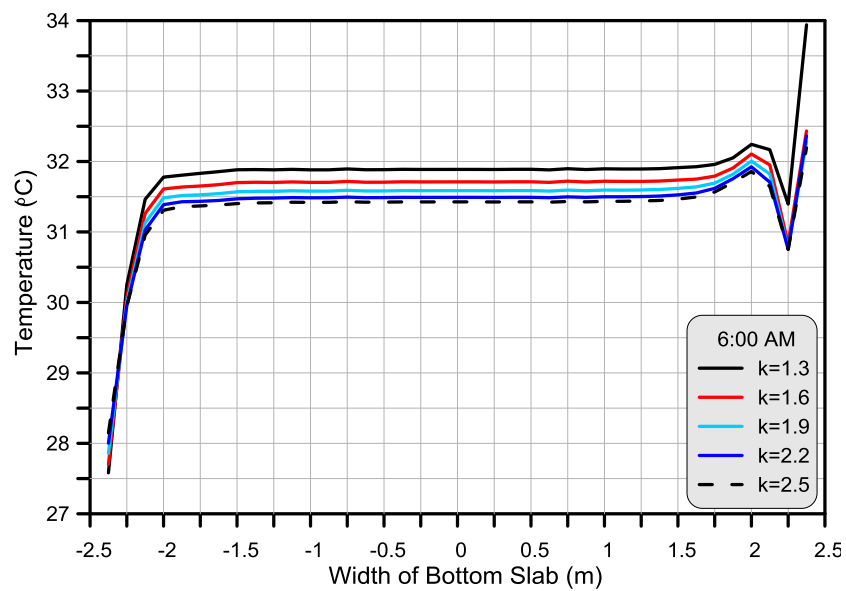


Figure 8.5 Thermal conductivity parametric study: temperature distributions along the bottom slab at 6:00 AM

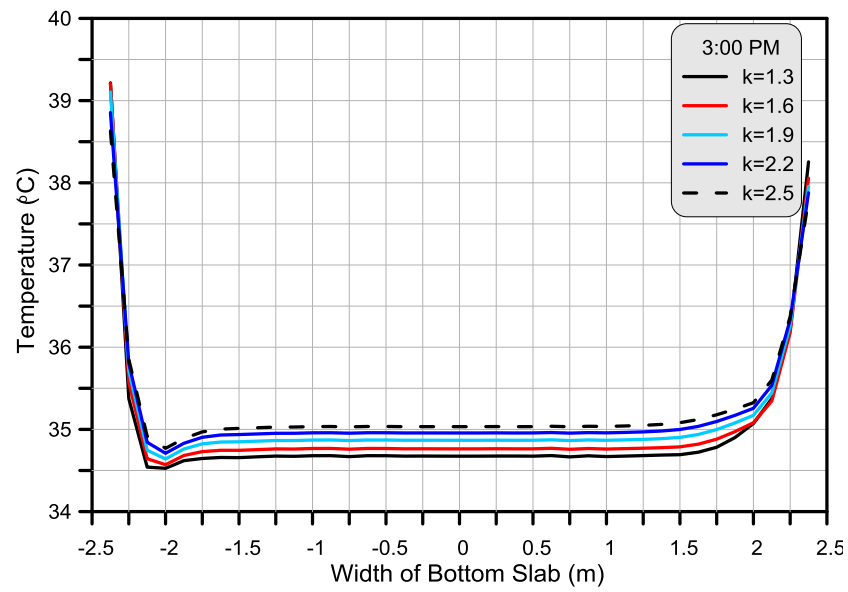


Figure 8.6 Thermal conductivity parametric study: temperature distributions along the bottom slab at 3:00 PM

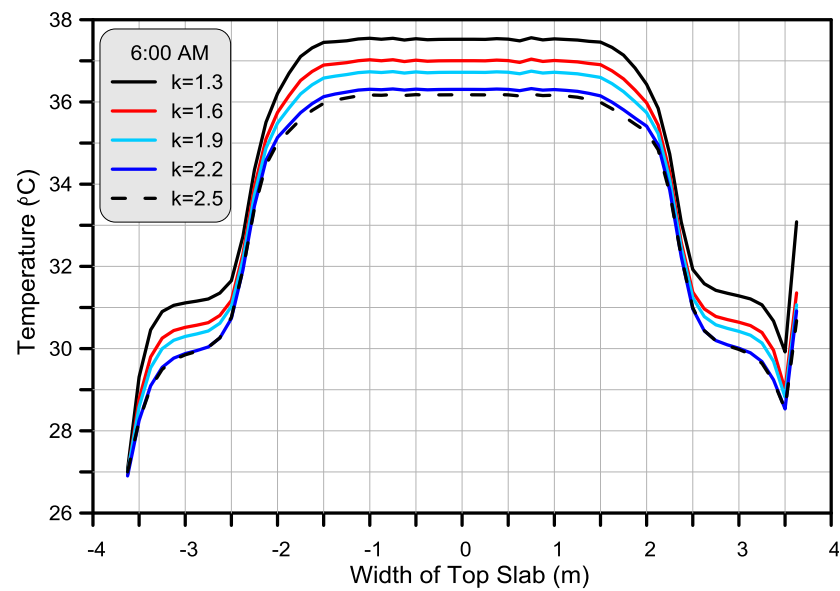


Figure 8.7 Thermal conductivity parametric study: temperature distributions along the top slab at 6:00 AM

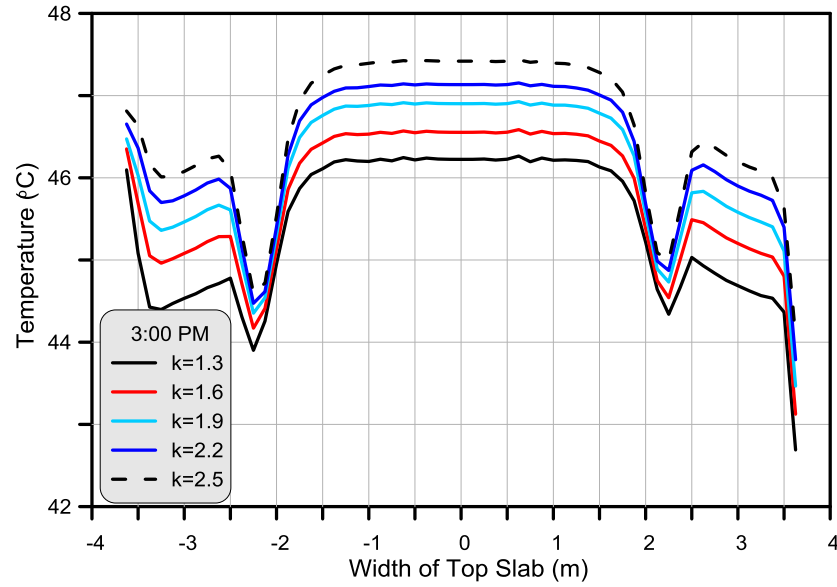


Figure 8.8 Thermal conductivity parametric study: temperature distributions along the top slab at 3:00 PM

8.4.1.2 Specific Heat

Figures 8.9 to 8.16 show the effect of the specific heat on the temperature distributions in the box-girder. The percentage differences across the top 200 mm of SW showed close values to those of thermal conductivity with a maximum value of 4.5% at the top surface as shown in Figure 8.10. For the case of temperature distributions across the thickness of the south web, the effect of specific heat was minimal as shown in Figures 8.11 and 8.12. For the bottom slab and as specific heat decreased from 1200 to 800 J/kg K, the recorded increase at 3:00 PM was 3.3% as shown in Figure 8.14, while the recorded decrease at 6:00 AM was 3.9% as shown in Figure 8.13.

It is clear from Figures 8.15 and 8.16 that the specific heat affected the top slab temperatures more than the thermal conductivity did. As specific heat decreased from 1200 to 800 J/kg K, a maximum temperature increase of approximately 7.5% occurred as shown in Figure 8.16. Similar to thermal conductivity, specific heat seems to influence the temperature distributions of TS at 6:00 AM more than at 3:00 PM. As shown in Figure 8.15, a maximum temperature decrease of approximately 9.2% occurred as the specific heat decreased from 1200 to 800 J/kg K.

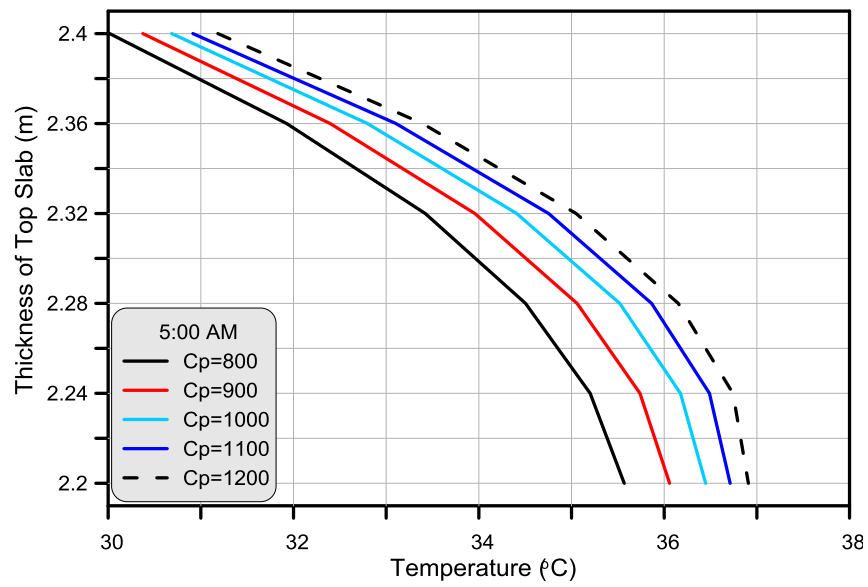


Figure 8.9 Specific heat parametric study: temperature distributions along the SW top 200 mm at 5:00 AM

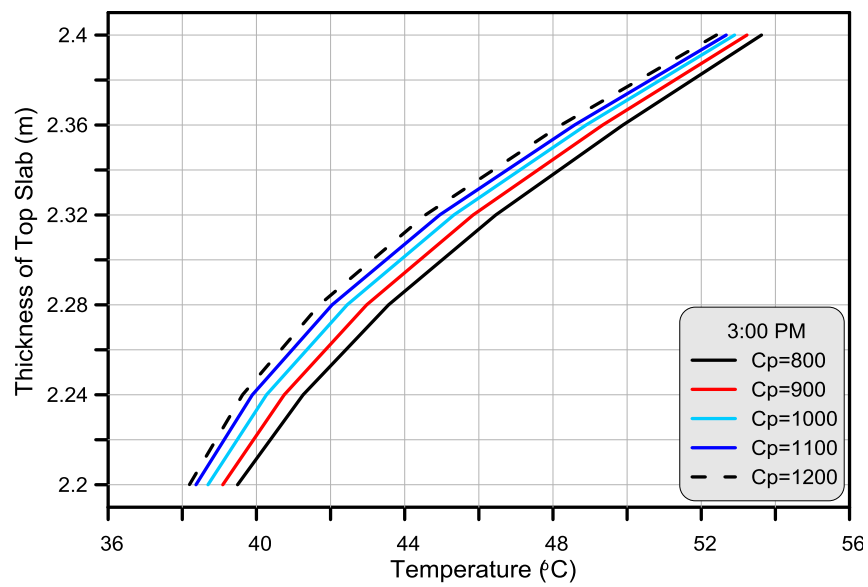


Figure 8.10 Specific heat parametric study: temperature distributions along the SW top 200 mm at 3:00 PM

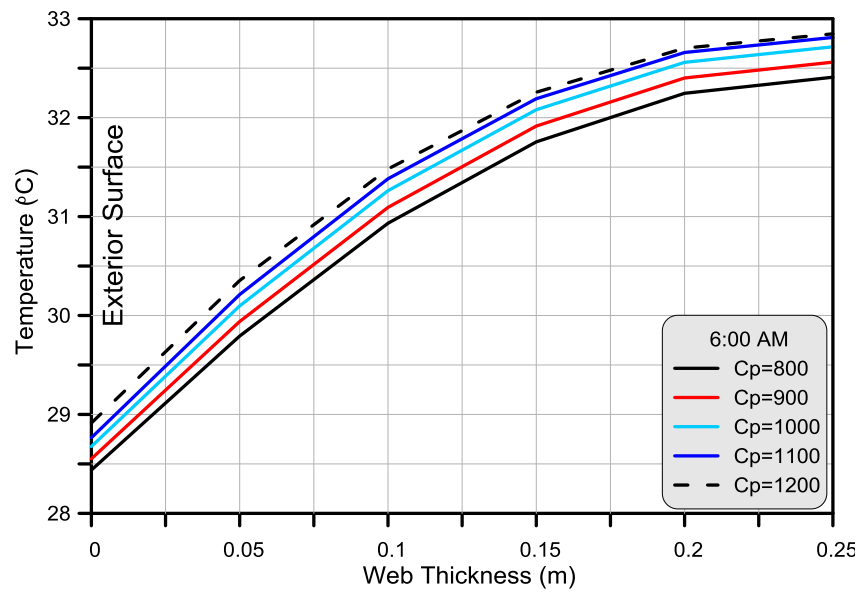


Figure 8.11 Specific heat parametric study: temperature distributions across the web at 6:00 AM

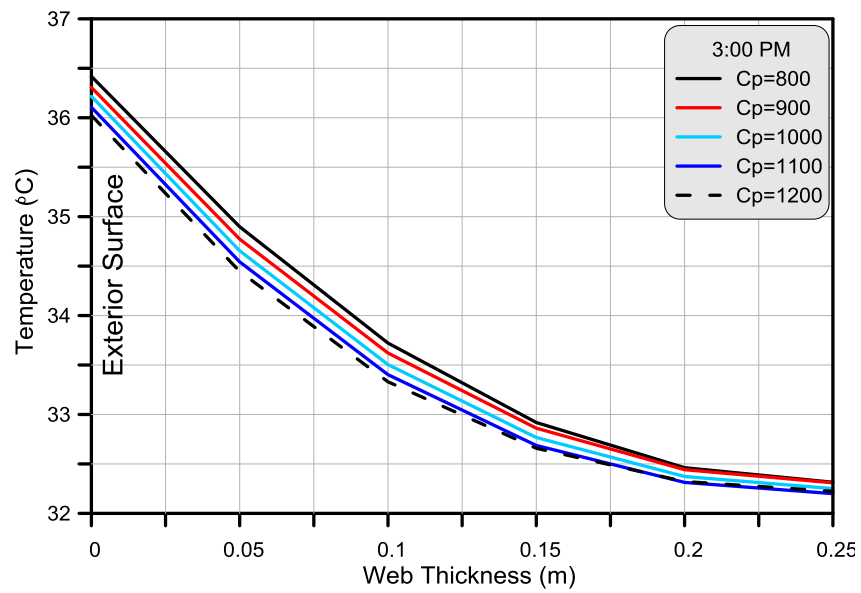


Figure 8.12 Specific heat parametric study: temperature distributions across the web at 3:00 PM

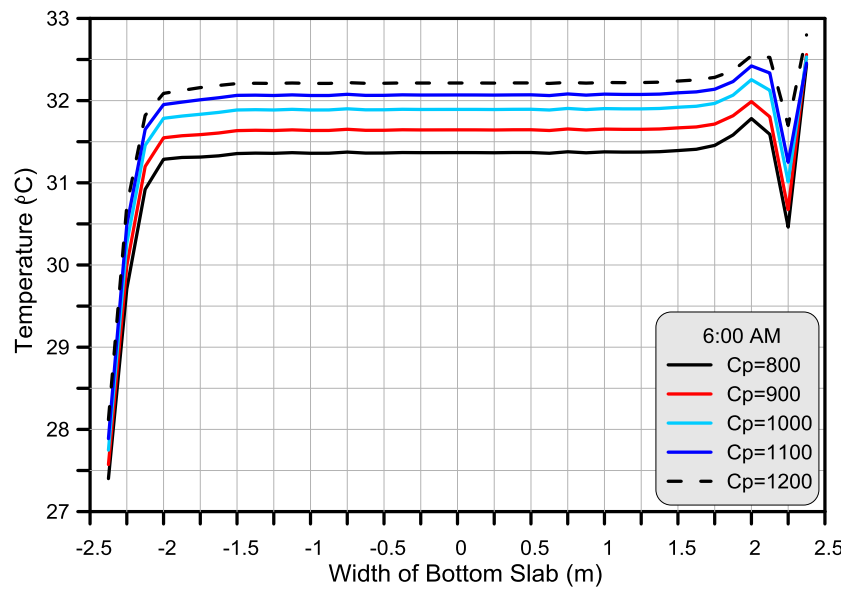


Figure 8.13 Specific heat parametric study: temperature distributions along the bottom slab at 6:00 AM

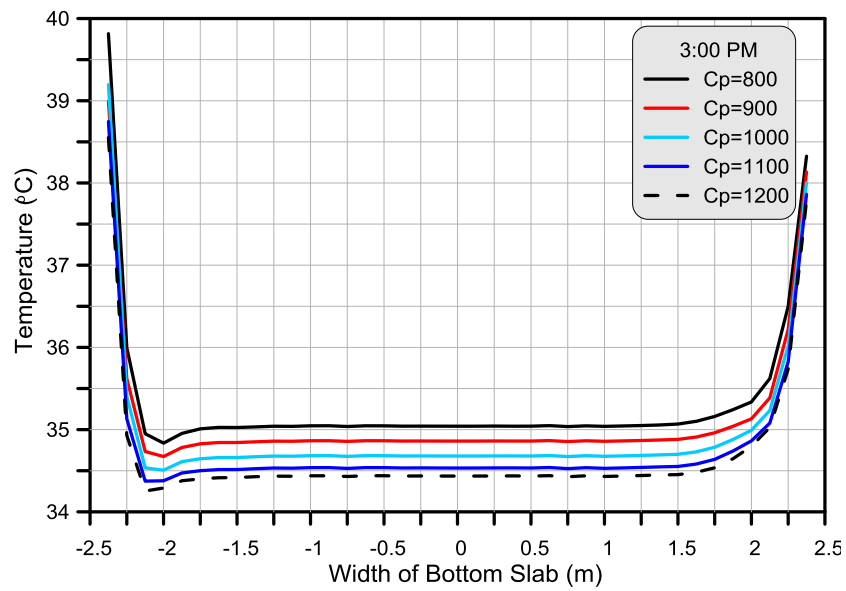


Figure 8.14 Specific heat parametric study: temperature distributions along the bottom slab at 3:00 PM

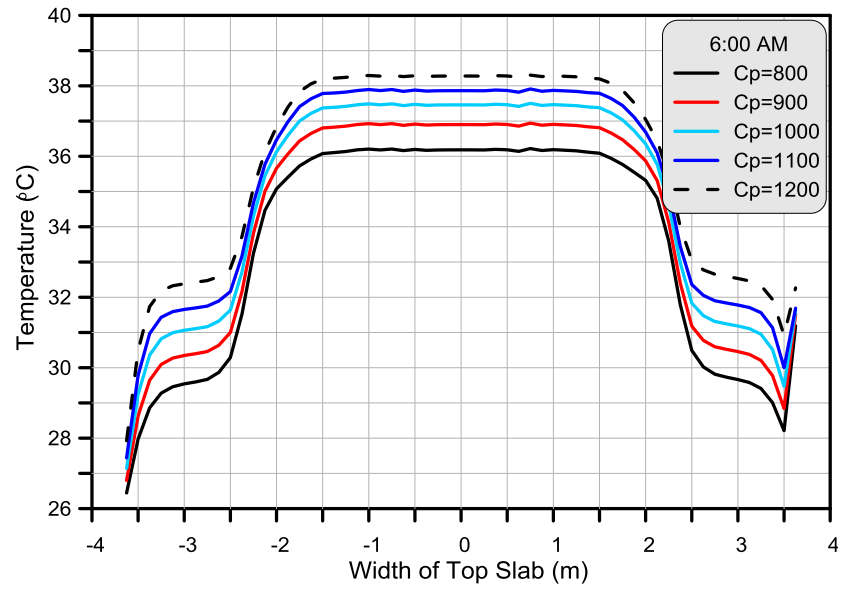


Figure 8.15 Specific heat parametric study: temperature distributions along the top slab at 6:00 AM

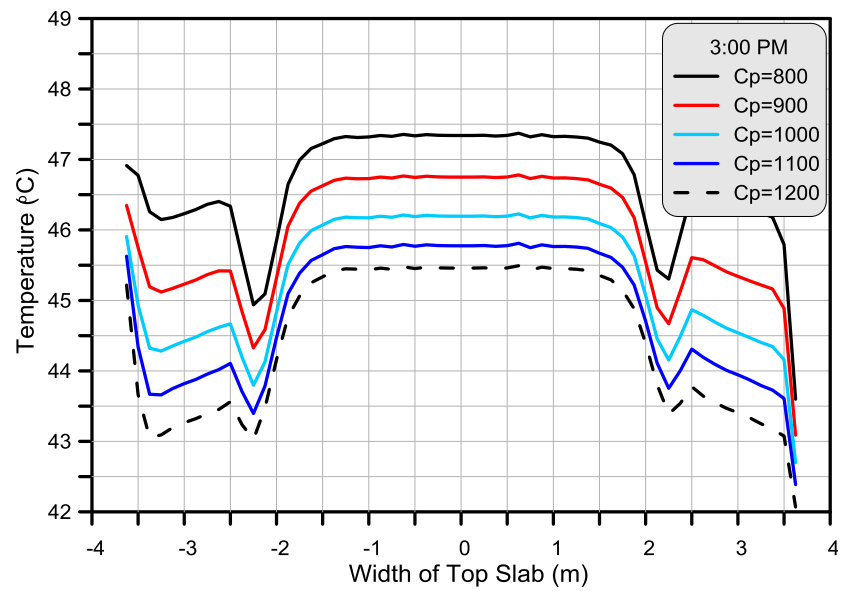


Figure 8.16 Specific heat parametric study: temperature distributions along the top slab at 3:00 PM

8.4.1.3 Solar Absorptivity

As concluded from the one-way ANOVA studies, which are summarized in Tables 8.5 and 8.6, the solar absorptivity found to affect the temperature distributions in the box-girder more than the rest thermal properties do.

Figures 8.17 and 8.18 show that the solar absorptivity influenced the temperature distributions across the top 200 *mm* of SW noticeably compared to Figures 8.1 and 8.2 (thermal conductivity) and Figures 8.9 and 8.10 (specific heat). The percentage increase values of the temperature at the top surface were 4%, 7.8%, 11.6%, and 15.7% as solar absorptivity increased from 0.5 to 0.55, 0.6, 0.65, and 0.7, respectively. Likewise, the percentages of temperature increase of the top slab were approximately 3.5%, 7%, 10.5%, and 14.1%, respectively, as shown in Figure 8.24. On the other hand, the maximum temperature increase across the thickness of the mid-height of the south web was 5.4 % as shown in Figure 8.20, while for the bottom slab, a maximum increase of approximately 7% took place at 3:00 PM as solar absorptivity increased from 0.5 to 0.7 as shown in Figure 8.22.

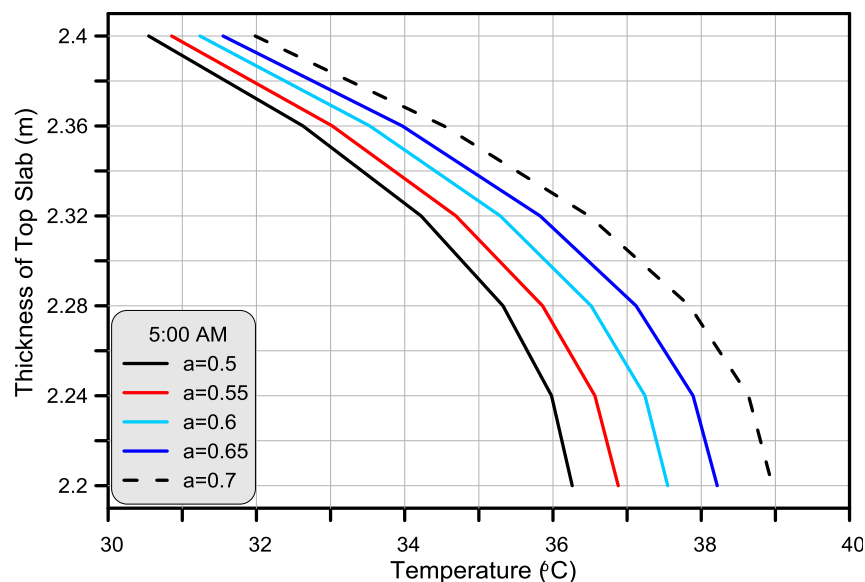


Figure 8.17 Surface absorptivity parametric study: temperature distributions along the SW top 200 *mm* at 5:00 AM

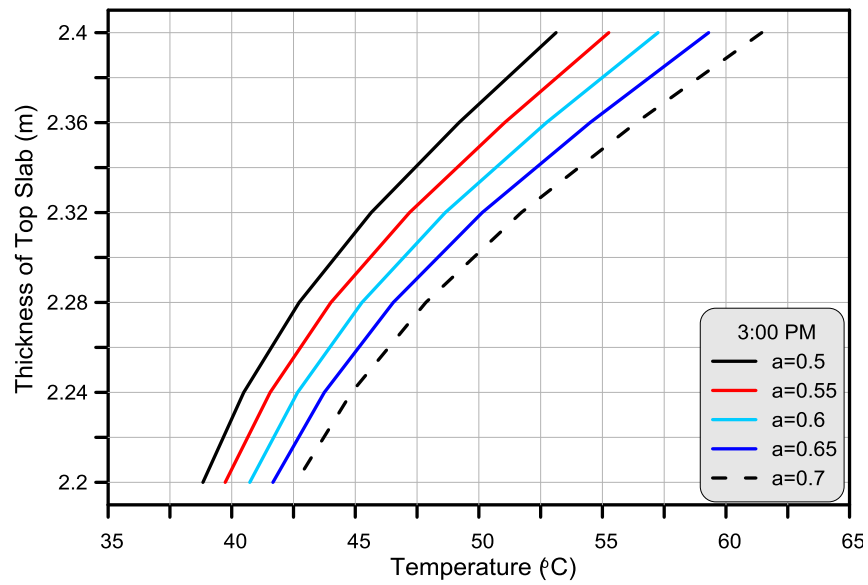


Figure 8.18 Surface absorptivity parametric study: temperature distributions along the SW top 200 *mm* at 3:00 PM

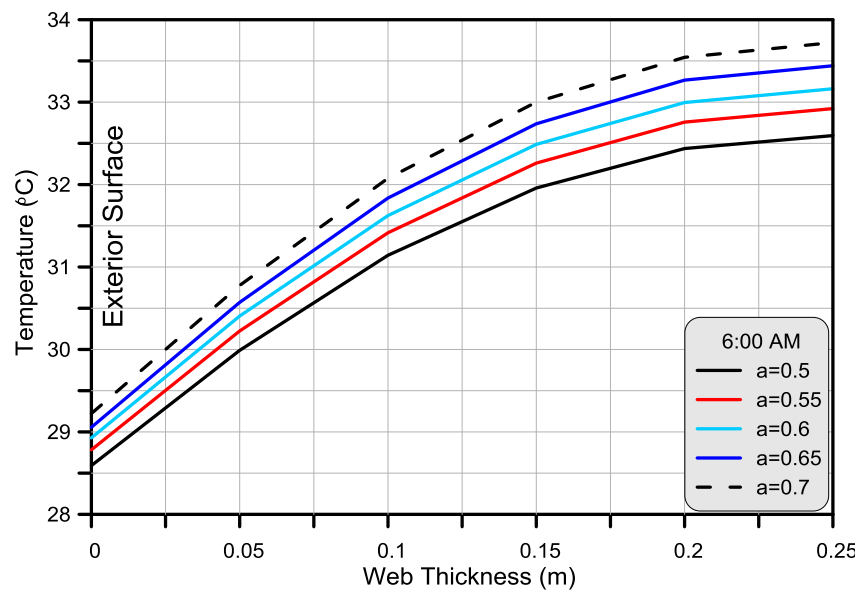


Figure 8.19 Surface absorptivity parametric study: temperature distributions across the web at 6:00 AM

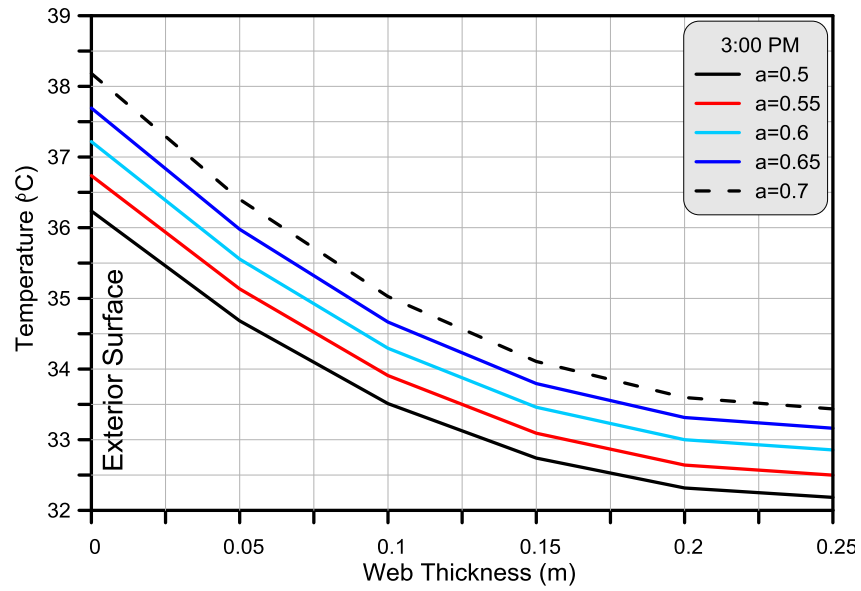


Figure 8.20 Surface absorptivity parametric study: temperature distributions across the web at 3:00 PM

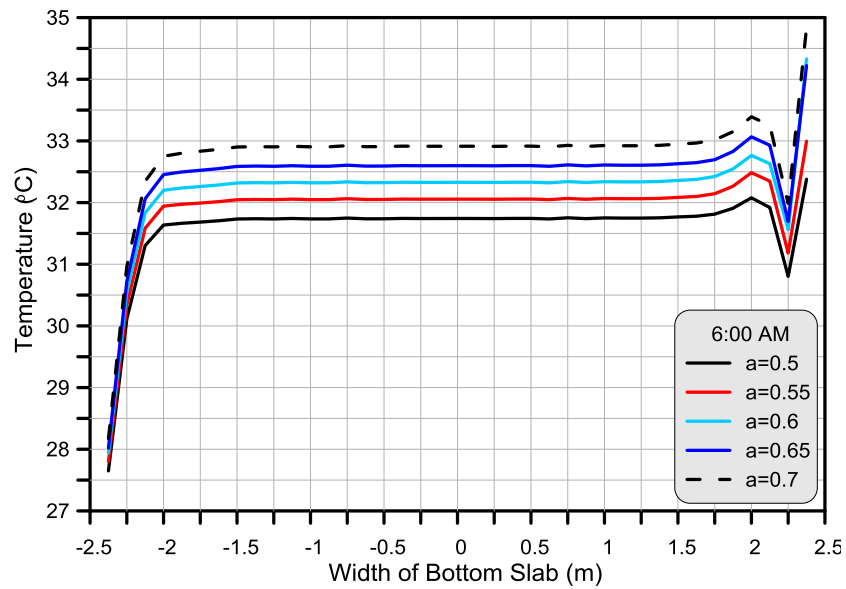


Figure 8.21 Surface absorptivity parametric study: temperature distributions along the bottom slab at 6:00 AM

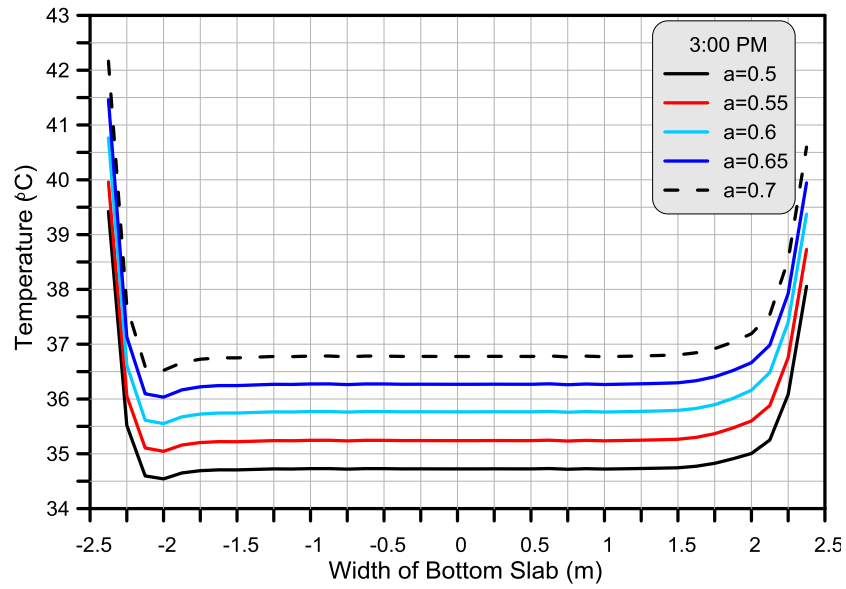


Figure 8.22 Surface absorptivity parametric study: temperature distributions along the bottom slab at 3:00 PM

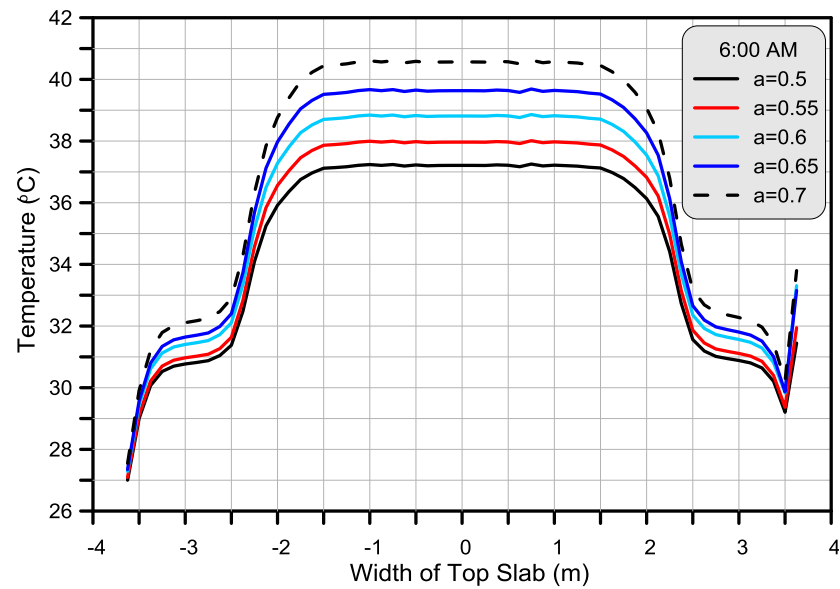


Figure 8.23 Surface absorptivity parametric study: temperature distributions along the top slab at 6:00 AM

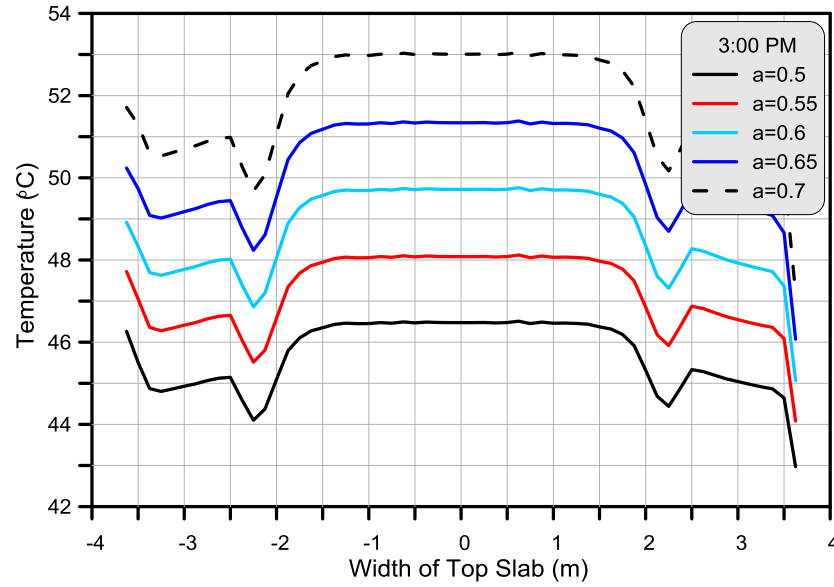


Figure 8.24 Surface absorptivity parametric study: temperature distributions along the top slab at 3:00 PM

8.4.2 The Global Parametric Study of Thermal Properties

In addition to the three individual parametric studies that were discussed in the previous sections, a global parametric study with three loops was conducted. The global parametric study aims to evaluate the combined effect of the three studied thermal properties, thus, the thermal conductivity, the specific heat, and the solar absorptivity on the temperature distributions along and across the different parts of the box-girder.

In the exterior loop of the global parametric study, the solar absorptivity decreases from 0.7 to 0.5 with values of 0.7, 0.6, and 0.5. The variable of the middle loop is the specific heat, which increases from 800 to 1200 $J/kg K$ with three step values of 800, 1000, and 1200 $J/kg K$. Finally, in the interior loop, the thermal conductivity changes with the values of 1.3, 1.9, and 2.5 $W/m K$. Figure 8.25 shows a visualized 3x3 matrix, which represents the summary of the global parametric study in terms of temperature distributions of the entire 3D box-girder segment. As shown in the figure, the second column represents the individual effect of solar absorptivity with constant specific heat and thermal conductivity. The second row represents the individual effect of specific heat, while solar absorptivity and thermal conductivity

are kept constant. The first column and the first row represent the combined effects of thermal conductivity with solar absorptivity and the combined effect of thermal conductivity with specific heat, respectively. The main diagonal of the matrix shows the combined effect of thermal conductivity, specific heat, and solar absorptivity.

It is obvious from Figure 8.25 that temperature increases as solar absorptivity increase, and as specific heat and thermal conductivity decrease. It is also clear in the figure that case 1 with $a = 0.7$, $C_p = 800$, and $k = 1.3$ resulted in the highest temperature records in the bridge segment with a maximum temperature of 64.85°C, while case 3 with $a = 0.5$, $C_p = 1200$, and $k = 2.5$ gave the minimum temperature distribution with a maximum of 51.73°C. Thus, a total percentage increase of 25.3% occurred as the three properties changed from case 3 to case 1. It is obvious that this percentage exceeds all of the individual percentage differences that were discussed previously for the individual parametric studies.

This result is also obvious in Figure 8.26, which shows the variation of the bridge maximum temperature during the 24 hours of 10-July-2013. On the other hand, Figure 8.27 shows that the variations between the minimum bridge temperatures of case 1, case 2, and case 3 were small along the full day. Thus, and as shown in Figure 8.28, the hourly difference between the maximum and minimum temperatures of the bridge increased. The maximum temperature differences for case 1, case 2, and case 3, which took place around 2:00 PM, were 32.2°C, 25.1°C, and 19.4°C, respectively. Thus, at 2:00 PM, a jump of approximately 64% occurred in the hourly temperature difference as thermal properties changed from case 3 to case 1. It should be addressed that the maximum percentage increase was recorded at 11:00 AM, which was about 70%.

Therefore, it can be said that the overall influence of the material properties can seriously change the temperature distributions in the box-girder, and thus it can affect the thermal behavior of the box-girder bridge.

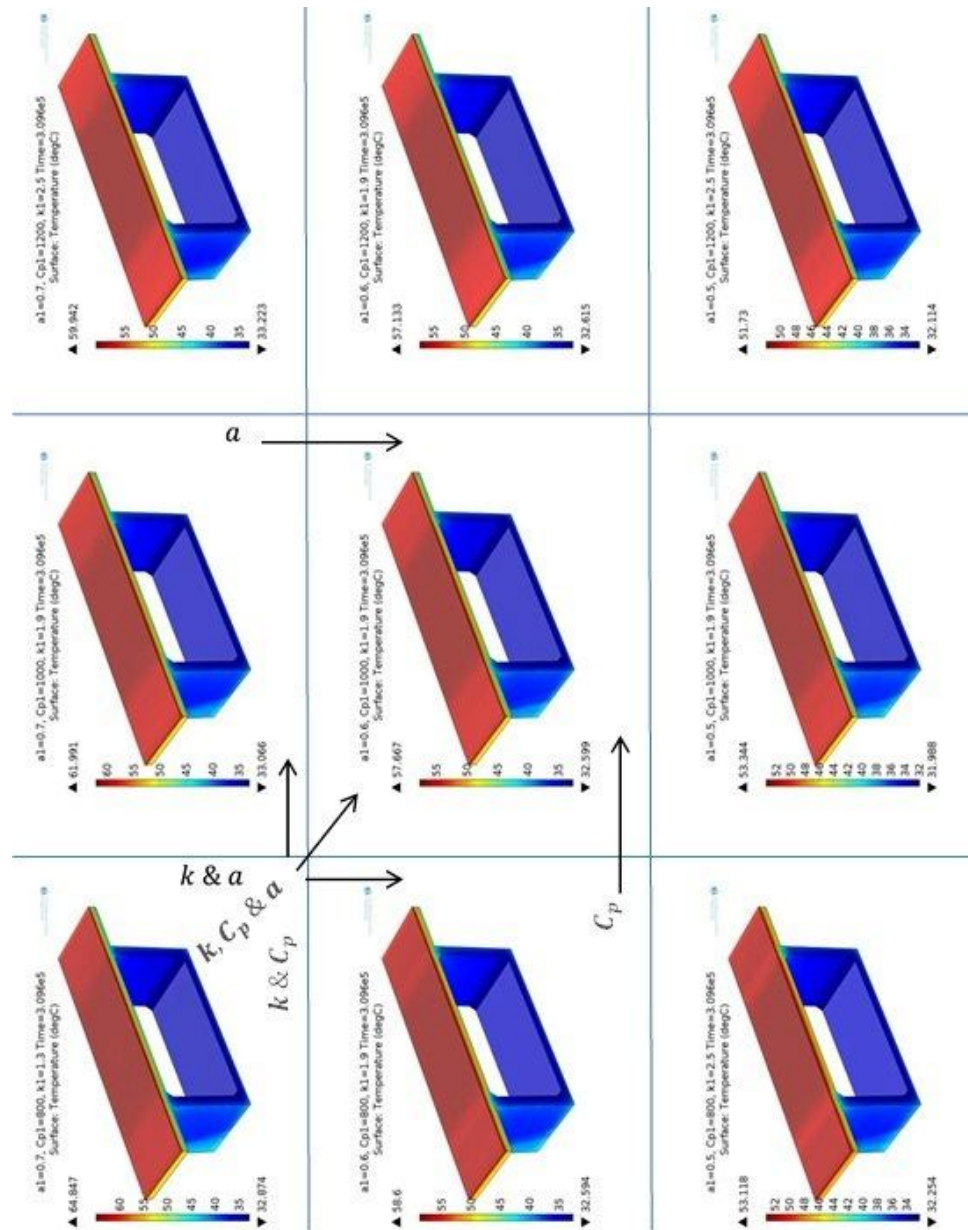


Figure 8.25 Global parametric study: temperature distribution in the box-girder segment

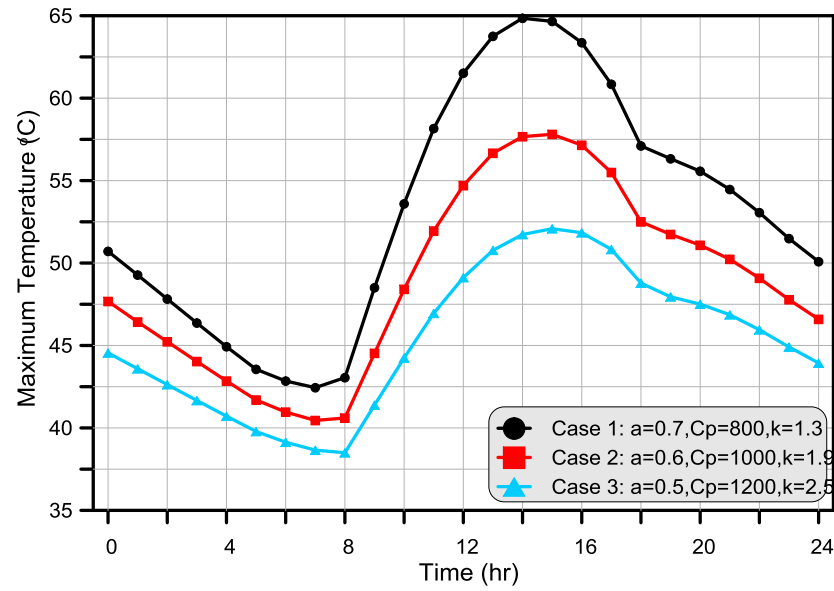


Figure 8.26 Variation of the bridge's maximum temperature during the 24 hours of 10-July-2013 for the three cases of the global parametric study

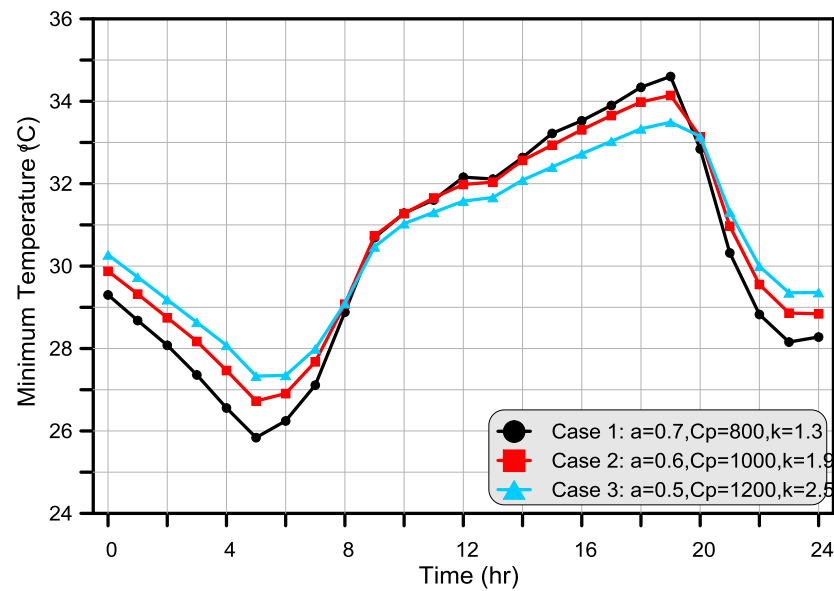


Figure 8.27 Variation of the bridge's minimum temperature during the 24 hours of 10-July-2013 for the three cases of the global parametric study

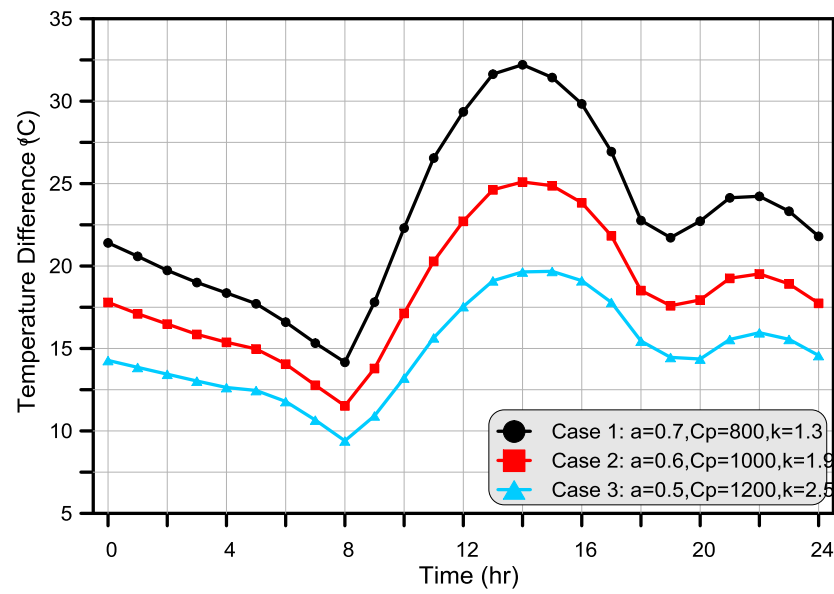


Figure 8.28 Variation of the temperature difference (maximum-minimum) during the 24 hours of 10-July-2013 for the three cases of the global parametric study

CHAPTER NINE

TEMPERATURES AND TEMPERATURE GRADIENTS IN TURKEY

9.1 General

Using the COMSOL finite element model that was verified in chapter six, the effect of air temperature and solar radiation on concrete bridges is studied for ten cities from the seven regions of turkey. This chapter focuses on the maximum vertical temperature gradient in addition to the mean, maximum, and minimum temperatures of concrete box-girder bridges.

9.2 The Selected Cities

The Turkish area is divided into seven different regions, four of which are coastal regions, while the rest three are inland regions. The four coastal regions are the Mediterranean, the Black Sea, the Marmara, and the Aegean, while the inland regions are the Central Anatolian, the Eastern Anatolian, and the Southeastern Anatolian. The ten cities were selected from different geographical locations so that they can represent the seven regions of turkey. The selected cities are Adana, Ankara, Antalya, Çorum, Diyarbakir, Istanbul, Izmir, Samsun, Şanlıurfa, and Şırnak. Table 9.1 lists the regions and the geographical locations of the selected cities, while Figure 9.1 shows the location of the selected cities on the Turkish map.

Table 9.1 The regions and geographical location of the selected cities

City	Region	Latitude	Longitude
Adana	Mediterranean	36.98 N	35.35 E
Antalya	Mediterranean	36.91 N	30.69 E
Ankara	Central Anatolian	39.95 N	32.88 E
Çorum	Black Sea	40.55 N	34.95 E
Diyarbakir	Southeastern Anatolian	37.89 N	40.20 E
Istanbul	Marmara	40.90 N	29.15 E
Izmir	Aegean	38.43 N	27.17 E
Samsun	Black Ssea	41.28 N	36.30 E
Şanlıurfa	Southeastern Anatolian	37.13 N	38.77 E
Şırnak	Eastern Anatolian	37.52 N	42.46 E



Figure 9.1 The location of the selected cities and their regions

9.3 Air Temperature and Solar Radiation Data of the Selected Cities

In the current analysis, temperature and solar radiation records for more than 50 years, from 1960 to 2013, were used to evaluate the extreme temperature and temperature gradients in concrete box girder bridges. The data were provided by the Turkish State Metrological Service [92]. The analysis was carried out for six months that represent the four seasons of the year, which are April, June, July, October, November, and December.

For each month, the day of the maximum daily air temperature difference was considered. The maximum air temperature difference was calculated based on the long-term recorded daily maximum air temperature and the long-term average daily minimum air temperature. For each of the six months, the long-term maximum daily average of total global solar radiation was considered. To maximize the

temperatures and temperature gradients, the wind speed was taken as zero. Tables 9.2 to 9.7 list the air temperature and solar radiation data of the ten cities in the six months, in which the presented solar radiation is the daily maximum hourly incidence on horizontal surface in W/m^2 .

Table 9.2 Solar radiation and air temperature of the 10 cities in April

City	Daily maximum hourly solar radiation W/m^2	Daily max air temperature °C	Daily min air temperature °C	Daily air temperature difference °C
Adana	938.66	35.6	11.6	24
Antalya	1023.9	32.5	14.5	18
Ankara	975.52	30.0	5.3	24.7
Çorum	865.27	30.4	3.8	26.6
Diyarbakir	989.59	35.3	7.8	27.5
Istanbul	816.43	32.9	8.7	24.2
Izmir	886.21	32.1	11.2	20.9
Samsun	858.29	37.0	7.7	29.3
Şanlıurfa	907.14	34.6	12.6	22
Şırnak	1041.7	29.0	8.1	20.9

Table 9.3 Solar radiation and air temperature of the 10 cities in June

City	Daily maximum hourly solar radiation W/m^2	Daily max air temperature °C	Daily min air temperature °C	Daily air temperature difference °C
Adana	960.87	40.8	18.5	22.3
Antalya	1075.1	35.8	18.6	17.2
Ankara	1002.74	35.3	11.6	23.7
Çorum	955.98	36.9	9.6	27.3
Diyarbakir	996.57	39.6	14.0	25.6
Istanbul	879.23	40.2	17.9	22.3
Izmir	935.05	38.7	18.0	20.7
Samsun	861.31	37.4	16.7	20.7
Şanlıurfa	921.09	44.0	19.3	24.7
Şırnak	1027.28	33.4	15.4	18

Table 9.4 Solar radiation and air temperature of the 10 cities in July

City	Daily maximum hourly solar radiation W/m^2	Daily max air temperature °C	Daily min air temperature °C	Daily air temperature difference °C
Adana	936.33	44	22.7	21.3
Antalya	1018.55	40.8	23.7	17.1
Ankara	996.11	40.8	16.6	24.2
Çorum	1004.83	42.6	13.4	29.2
Diyarbakir	1008.55	44.7	21.7	23
Istanbul	886.21	39.7	19.4	20.3
Izmir	921.09	42.6	22.4	20.2
Samsun	830.38	36.1	18.4	17.7
Şanlıurfa	955.98	46.8	25.0	21.8
Şırnak	1002.62	40.4	22.9	17.5

Table 9.5 Solar radiation and air temperature of the 10 cities in October

City	Daily maximum hourly solar radiation W/m^2	Daily max air temperature °C	Daily min air temperature °C	Daily air temperature difference °C
Adana	798.63	38	15.8	22.2
Antalya	818.98	34.9	17.5	17.4
Ankara	732.22	31.4	8.4	23
Çorum	683.84	33.0	6.8	26.2
Diyarbakir	753.62	31.0	8.2	22.8
Istanbul	655.93	34.2	13.5	20.7
Izmir	732.69	33.2	13.5	19.7
Samsun	648.95	38.4	14.0	24.4
Şanlıurfa	767.58	34.8	14.4	20.4
Şırnak	806.07	27.4	10.7	16.7

Table 9.6 Solar radiation and air temperature of the 10 cities in November

City	Daily maximum hourly solar radiation W/m^2	Daily max air temperature °C	Daily min air temperature °C	Daily air temperature difference °C
Adana	588.59	32.6	10.9	21.7
Antalya	641.04	28.9	11.7	17.2
Ankara	585.8	23.6	2.7	20.9
Çorum	551.26	25.0	2.3	22.7
Diyarbakir	690.82	24.3	3.7	20.6
Istanbul	537.30	27.2	9.9	17.3
Izmir	655.93	28.8	10.7	18.1
Samsun	516.37	28.8	8.0	20.8
Şanlıurfa	635	27.3	7.3	20
Şırnak	641.28	22.6	4.2	18.4

Table 9.7 Solar radiation and air temperature of the 10 cities in December

City	Daily maximum hourly solar radiation W/m^2	Daily max air temperature °C	Daily min air temperature °C	Daily air temperature difference °C
Adana	551.38	30.8	8.6	22.2
Antalya	567.54	26.8	11.5	15.3
Ankara	529.05	19.8	0.7	19.1
Çorum	565.22	18.0	-2.5	20.5
Diyarbakir	621.04	18.0	-1.2	19.2
Istanbul	516.37	25.5	7.4	18.1
Izmir	537.31	24.7	7.1	17.6
Samsun	411.7	26.9	5.7	21.2
Şanlıurfa	509.39	26.0	5.4	20.6
Şırnak	588.48	19.0	0.5	18.5

9.4 Temperatures and Temperature Gradients in the Six Months

Before the comparison of the different temperature gradients for the ten cities, the variation of the gradients along the depth of the box-girder and across the thickness of the top and bottom slabs, in addition to the variation of the average, the maximum, and the minimum temperatures of the bridge with time are discussed in this section. For better presentation, the visualized results were reduced to include two cities only, one from the hot south region of Turkey, which is Adana, while the second is Samsun, which represent the cold Black Sea region.

The same geometry of the experimental box-girder, which was described in chapter three is used here. The conducted finite element model was similar to that described in chapter six. The vertical temperature gradients were calculated along the centerlines of the south and north webs and across the thicknesses of the top and bottom slabs. Figure 9.2 shows the four cross-sections, along which the vertical temperature gradients were calculated.

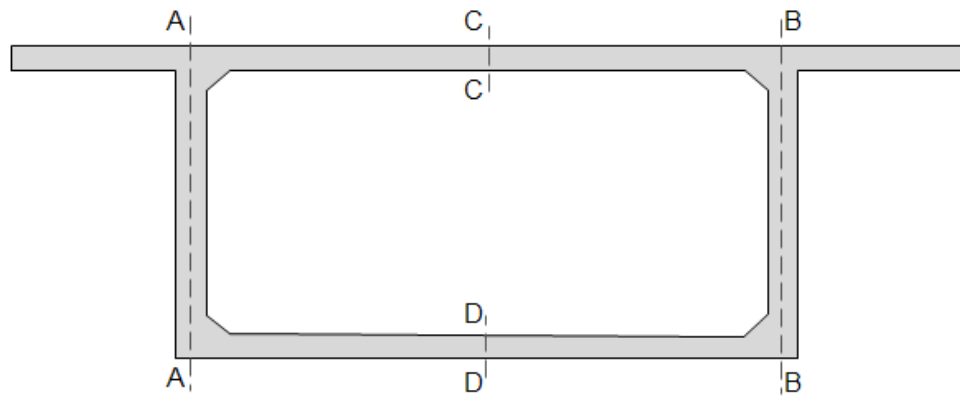


Figure 9.2 Sections of vertical temperature gradients

9.4.1 Vertical Temperature Gradients

Figures 9.3 to 9.10 show the vertical temperature gradients along the depth of the box girder (sections A and B) for Adana and Samsun in the six months. By the comparison between Figures 9.3 and 9.5, it is obvious that the shape of the positive gradient variation with the depth along section A is almost the same for both cities. The only recognized difference is the values of the maximum gradients at the top

and bottom surfaces. The maximum vertical positive gradients along section A in April, June, July, October, November, and December in Adana were 22.5, 25.5, 24.3, 11.7, 7.7, and 6.8°C, respectively. On the other hand, their corresponding values for Samsun were 19.3, 22.3, 19.7, 11.7, 6.0, and 5.4°C, respectively. Comparing the maximum positive gradients at the bottom surface for the two cities, Figures 9.3 and 9.5 show that excluding April, the same sequence was recorded as for the top surface's temperature gradient, where Adana showed higher temperature gradients than Samsun. However, in April, the gradient at the bottom surface was 9.0°C for Samsun, while it was 7.8°C for Adana.

A common notice for the two cities, is that the behavior of the gradient variation along the depth is the same during the hot season months (April, June, and July), while this behavior completely differs from the gradient variation behavior during the cold season (October, November, and December), as shown in Figures 9.3 and 9.5.

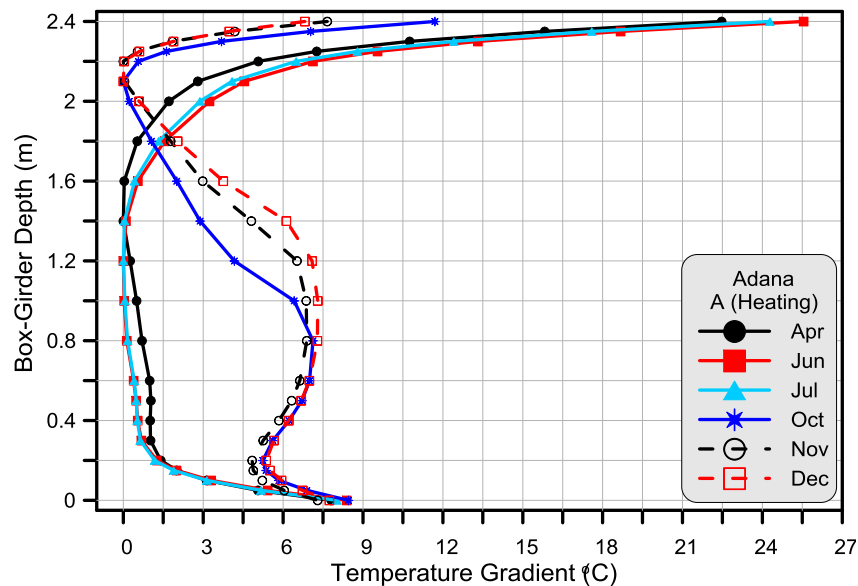


Figure 9.3 Maximum vertical positive temperature gradients along section A for the six months in Adana

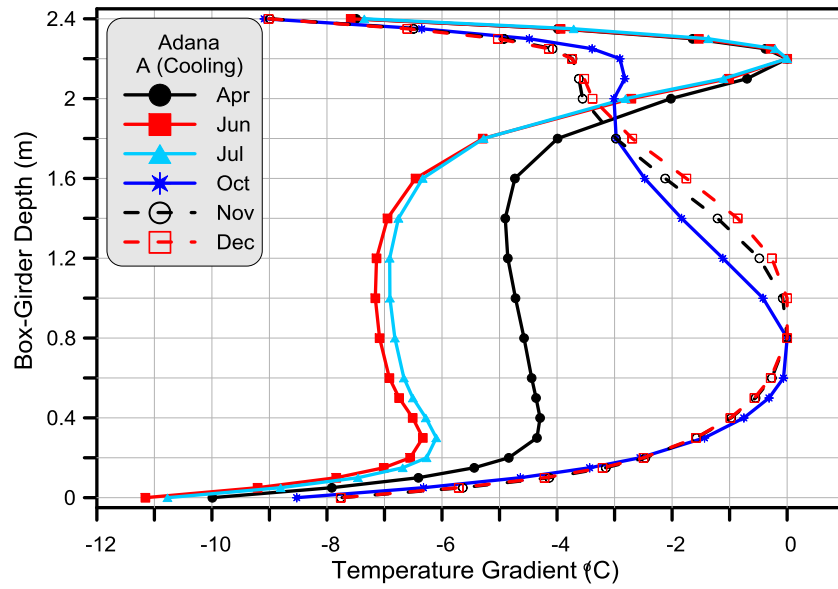


Figure 9.4 Maximum vertical negative temperature gradients along section A for the six months in Adana

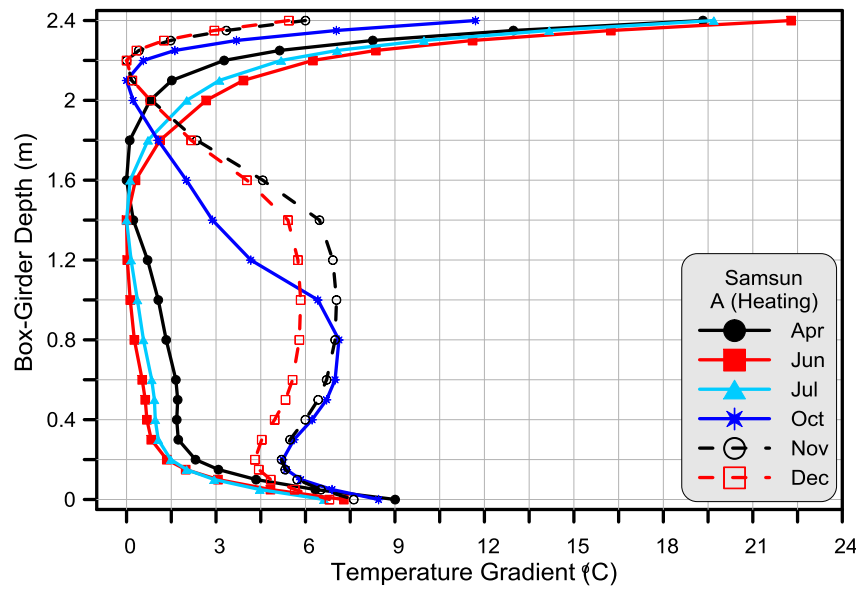


Figure 9.5 Maximum vertical positive temperature gradients along section A for the six months in Samsun

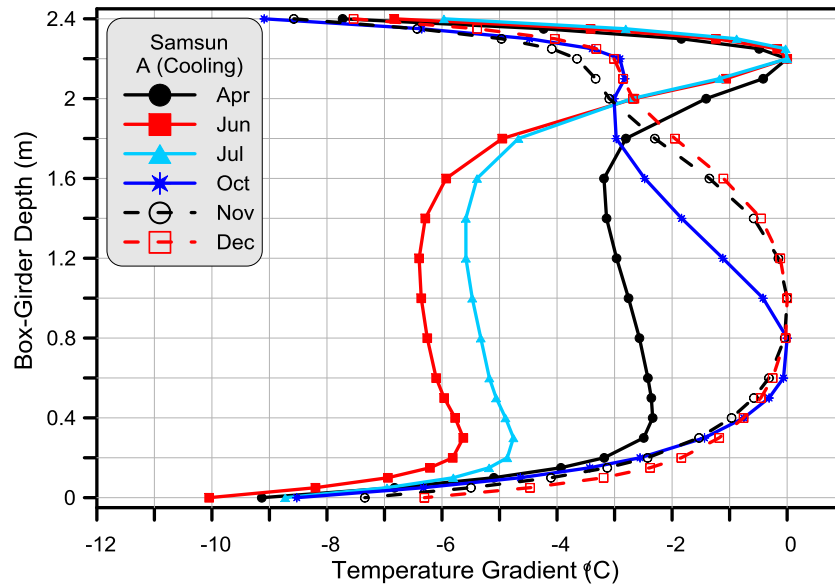


Figure 9.6 Maximum vertical negative temperature gradients along section A for the six months in Samsun

As for the positive gradient, the negative gradients along section A showed similar behavior for both Adana and Samsun as shown in Figures 9.4 and 9.6. In April, June, and July, the gradient at the bottom surface was greater than at the top surface. In addition, the maximum temperature gradient variation occurred across the thickness of the top slab with zero gradient at or near the bottom surface of the top slab.

The negative gradients along section A in October, November, and December showed different behavior. In these months, the temperature gradient at the top surface was slightly higher than at the bottom surface, while the zero temperature gradient occurred near the center of the web as shown in Figures 9.4 and 9.6. The maximum negative gradients at the top surface in April, June, July, October, November, and December in Adana were -7.5, -7.6, -7.3, -9.1, -9.0, and -9.0°C, respectively. At the bottom surface on the other hand, the negative gradients were -10, -11.2, -10.8, -8.5, -7.8, and -7.8°C, respectively. Similar sequences were also recorded for Samsun, but with different values.

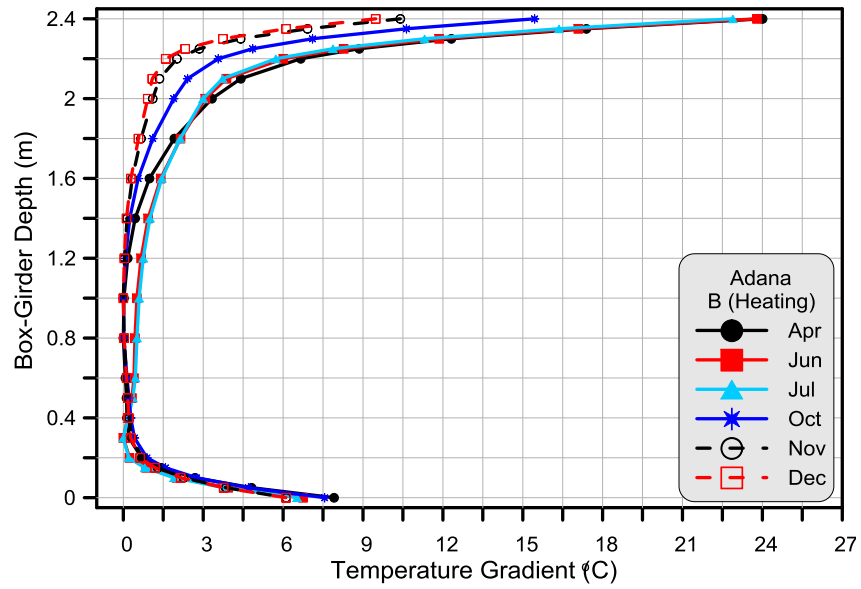


Figure 9.7 Maximum vertical positive temperature gradients along section B for the six months in Adana

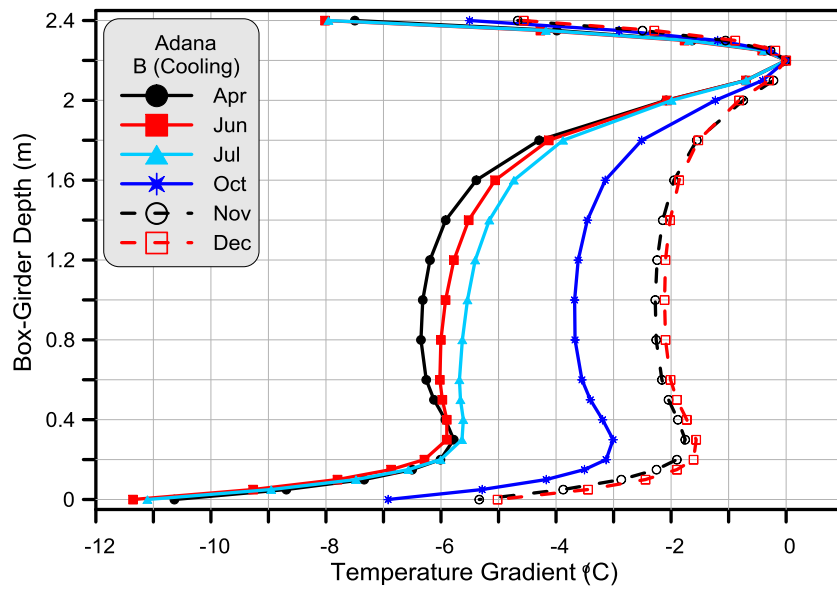


Figure 9.8 Maximum vertical negative temperature gradients along section B for the six months in Adana

As discussed above for section A, the positive and negative gradients were stable along the central depth of the web during the hot season, while in winter and autumn, the gradient was variable along this region. However, along section B, the gradient behavior was similar for all months both for the positive gradients (Figures 9.7 and 9.9) and for the negative gradients (Figures 9.8 and 9.10). The gradient

stability along section B, which was taken along the north web, is attributed to the effect of the uniform shading. In summer, the sun strikes the north web during the early morning hours and the early evening hours, while during the midday hours, the sun strikes the south web keeping the north web fully shaded. In winter, the sun strikes the south web along the whole day, while the north web is completely shaded along the full day hours. Therefore, the gradients along the north web (section B) show stable behaviors along the full year.

As shown in Figures 9.7, the maximum positive temperature gradients at the top surface for Adana were 24, 23.8, 22.9, 15.4, 10.4, and 9.5°C in April, June, July, October, November, and December, respectively. On the other hand, as shown in Figure 9.9, the maximum positive temperature gradients at the top surface for Samsun in April, June, July, October, November, and December were 21.8, 21.3, 19.8, 13.5, 8.0, and 7.1°C, respectively.

The negative temperature gradients along section B seems to be more stable in winter and autumn than in summer and spring along the mid-depth of the web as shown in Figures 9.8 and 9.10. As for during the hot season, the zero gradients occurred at the bottom surface of the top slab, but the gradients at or near the top surface of the bottom slab were also close to zero.

The maximum negative temperature gradients at the top surface of section B for Adana in April, June, July, October, November, and December were -7.5, -8.0, -7.9, -5.5, -4.7, and -4.6°C, respectively. Similarly, the maximum negative gradients for Samsun in April, June, July, October, November, and December were -7.5, -7.4, -6.3, -5.6, -4.2, and -4.0°C, respectively.

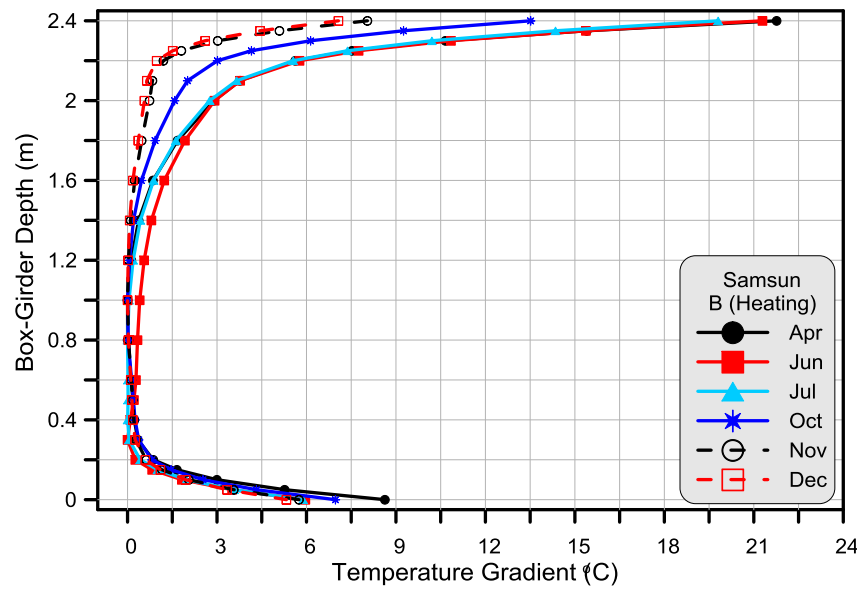


Figure 9.9 Maximum vertical positive temperature gradients along section B for the six months in Samsun

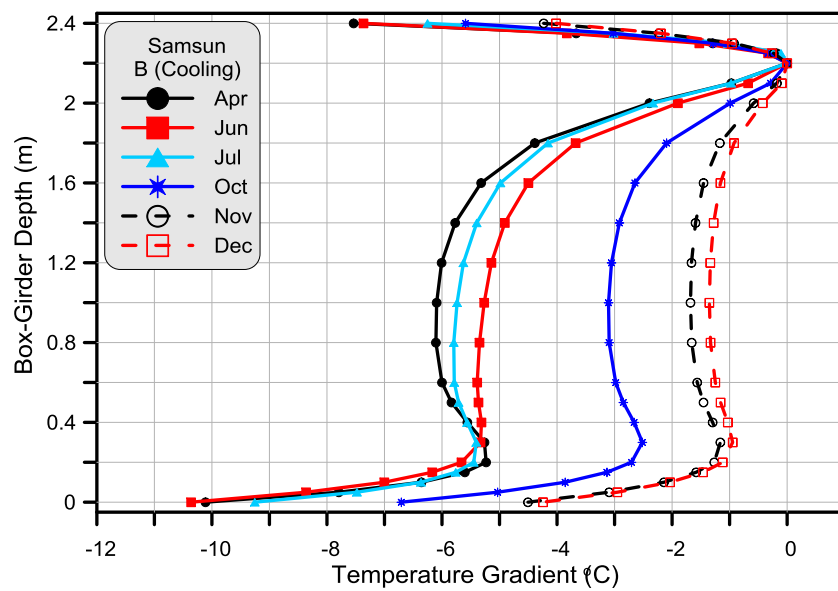


Figure 9.10 Maximum vertical negative temperature gradients along section B for the six months in Samsun

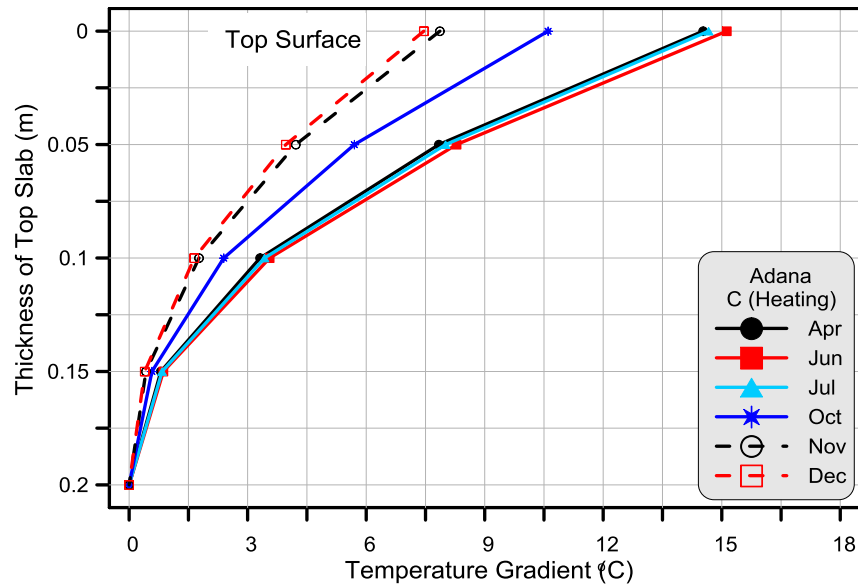


Figure 9.11 Maximum vertical positive temperature gradients along section C for the six months in Adana

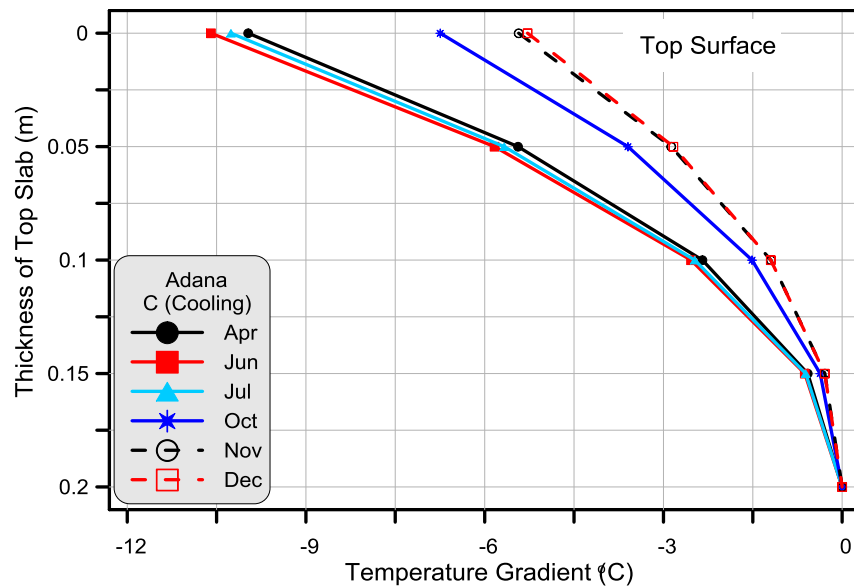


Figure 9.12 Maximum vertical negative temperature gradients along section C for the six months in Adana

The temperature gradient across the thickness of the top slab at its mid-span is important to estimate the thermal stresses accurately for this large area, which has longer moment arm than all other parts above the center of gravity of the box-girder. Figures 9.11 and 9.12 show the variations of the positive and negative temperature

gradients along section C for Adana, while Figures 9.13 and 9.14 show their corresponding gradients for Samsun.

As shown in Figures 9.11 and 9.13, the positive temperature gradients across section C have uniform variation and their values depend mainly on the quantity of solar radiation absorbed from the top surface and the daily air temperature difference. As shown in Figure 9.11, the positive temperature gradients at the top surface in April, June, July, October, November, and December for Adana were 14.5, 15.1, 14.7, 10.6, 7.9, and 7.5°C, respectively. Similarly, Figure 9.13 shows that the maximum positive temperature gradients for Samsun were 13.8, 13.0, 11.8, 9.5, 6.6, and 6.0°C in April, June, July, October, November, and December, respectively.

As shown, the maximum gradient in April was higher than in June, this is because the solar radiations of the simulated days were close, while the daily temperature difference was much higher in April. The daily maximum hourly solar radiation for April was 858 W/m^2 , while it was 861 W/m^2 for June. On the other hand, the daily air temperature differences for April and June were 29.3°C and 20.7°C, respectively.

The negative gradients along section C have also uniform variation as shown in Figures 9.12 and 9.14. The maximum top surface negative gradients for Adana were -10.0, -10.6, -10.3, -6.7, -5.4, and -5.3°C in April, June, July, October, November, and December, respectively, while the maximum top surface negative gradients for Samsun were -9.8, -9.5, -8.6, -6.7, -4.7 and -4.5°C, respectively for the same sequence of months.

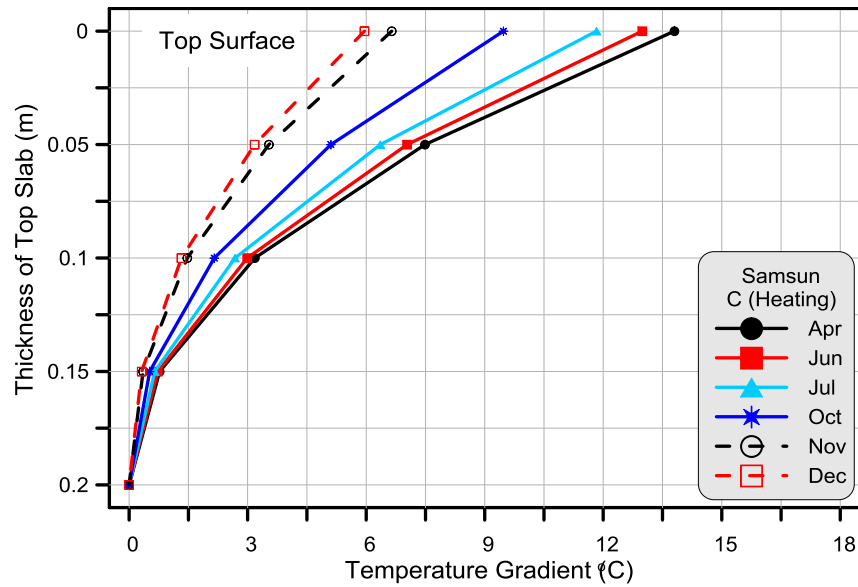


Figure 9.13 Maximum vertical positive temperature gradients along section C for the six months in Samsun

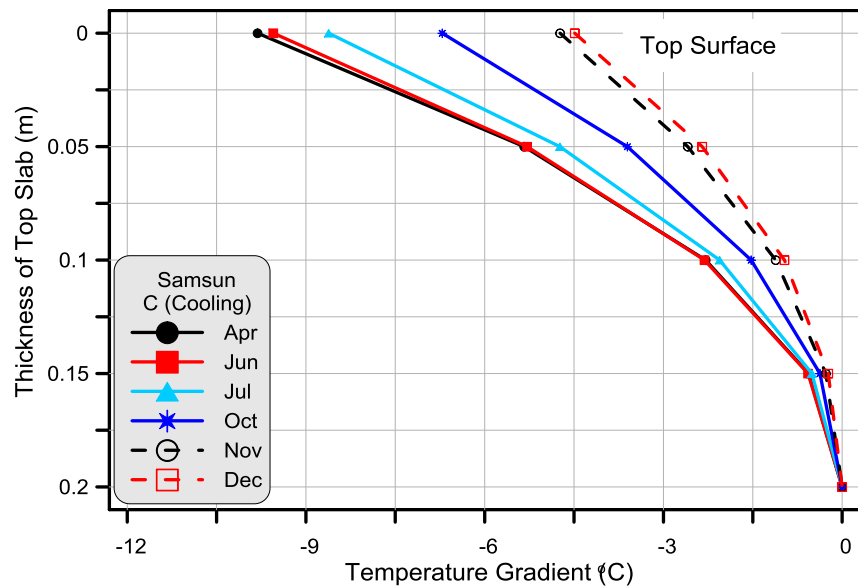


Figure 9.14 Maximum vertical negative temperature gradients along section C for the six months in Samsun

The temperature gradient across the mid-width thickness of the bottom slab (section D) show similar uniform variation to that along section C. Figures 9.15 through 9.18 show the positive and negative temperature gradients along section D for both Adana and Samsun.

As recorded for section C, the gradients along section D were higher in the hot season than in the cold season. In general, the maximum gradients at the bottom surface (section D) were lower than the gradients at the top surface (section C). As shown in Figure 9.15, the maximum positive gradients at the bottom surface for Adana were 6.8, 6.7, 6.6, 6.1, 5.0, and 5.1°C in April, June, July, October, November, and December, respectively. On the other hand, the maximum negative gradients at the bottom surface for the same sequence of months were -5.0, -5.1, -5.0, -4.3, -3.8, and -3.7, respectively, as shown in Figure 9.16. For Samsun, the maximum positive and negative gradients at the bottom surface showed similar sequences of variation with minor deviations as shown in Figures 9.17 and 9.18.

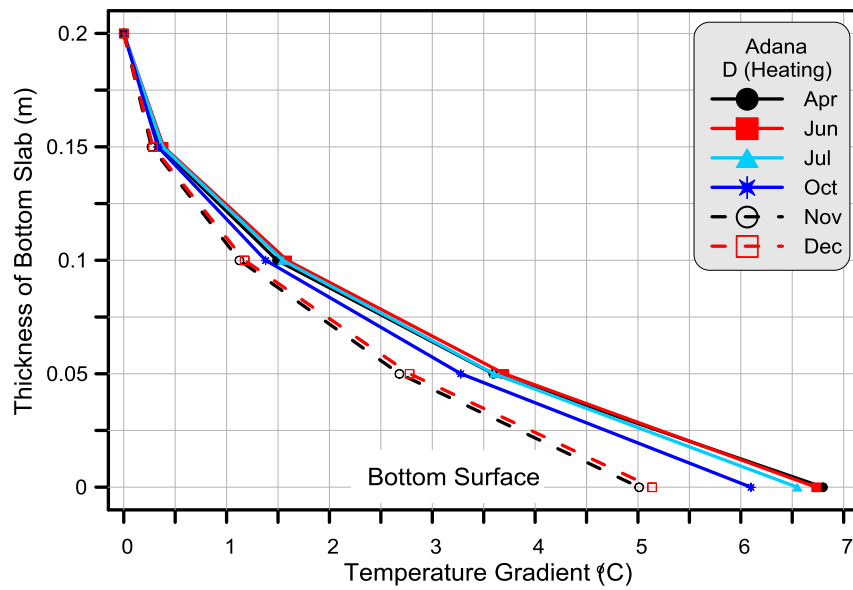


Figure 9.15 Maximum vertical positive temperature gradients along section D for the six months in Adana

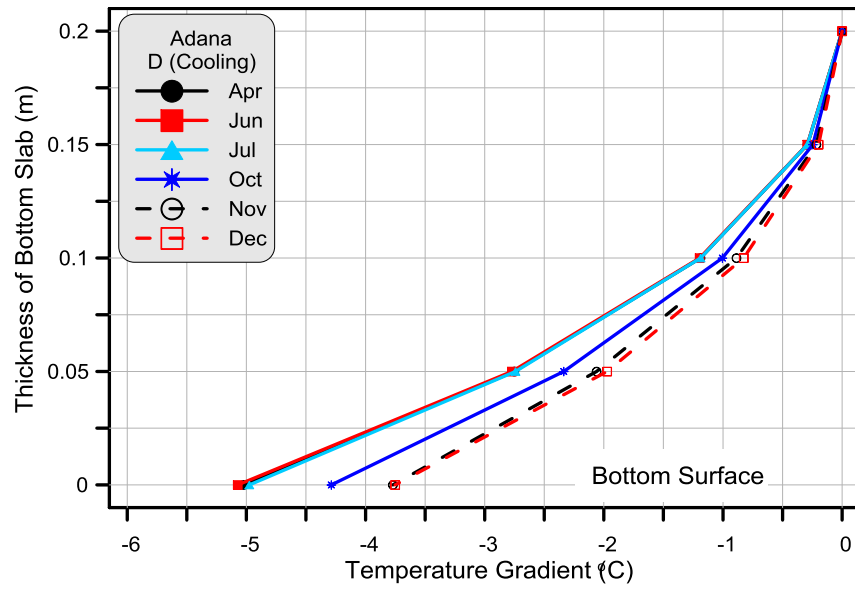


Figure 9.16 Maximum vertical negative temperature gradients along section D for the six months in Adana

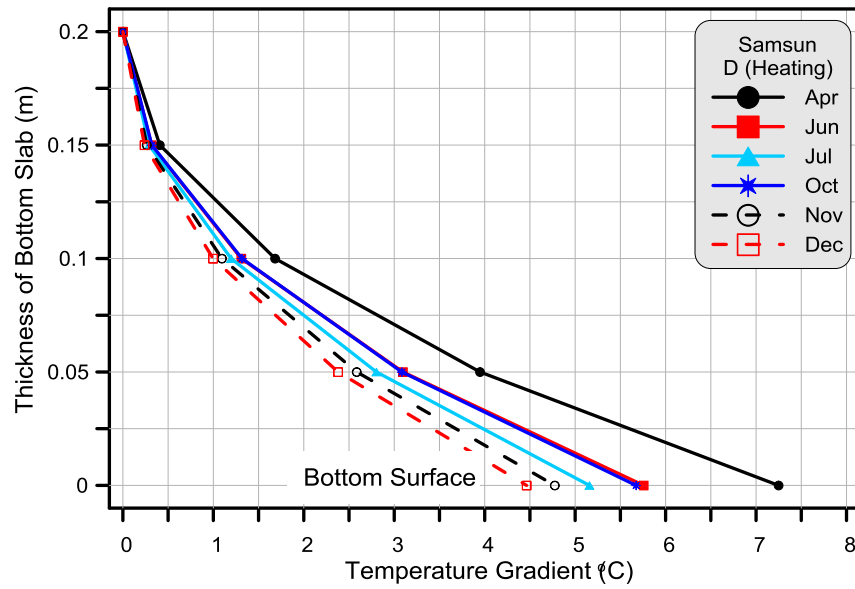


Figure 9.17 Maximum vertical positive temperature gradients along section D for the six months in Samsun

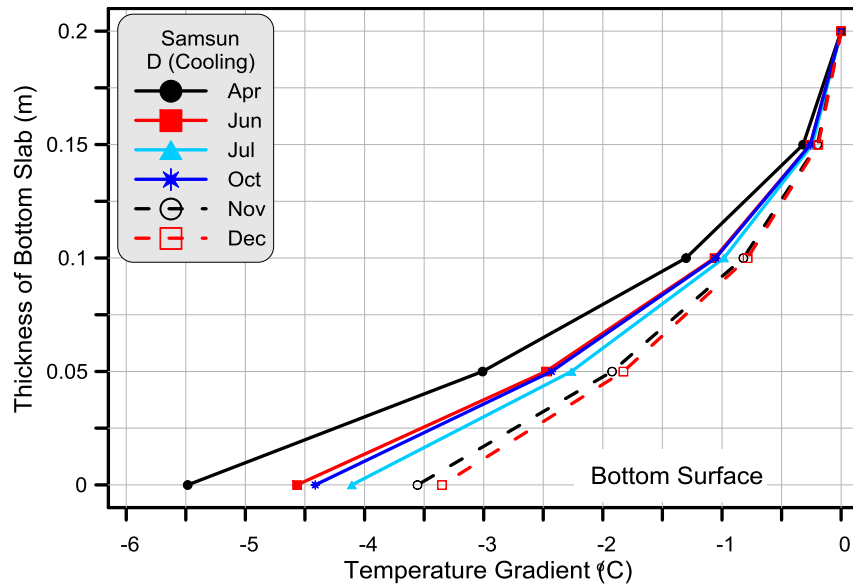


Figure 9.18 Maximum vertical negative temperature gradients along section D for the six months in Samsun

9.4.2 Average, Maximum, and Minimum Temperatures of the Box-Girder

The variations of the average, maximum, and minimum temperatures of the bridge are shown in Figures 9.19 through 9.24 for the 24 hours of the simulated days of the six months for both Adana and Samsun. It is shown that for the average, the maximum, and the minimum temperatures, the figures can be divided into three regions. The temperatures of June and July were the highest, while the temperatures of April and October came after, and finally, November and December exhibited the lowest temperatures. Another notice is that the maximum temperature of the bridge (Figures 9.20 and 9.23) showed higher daily variation than the average and the minimum temperatures. Since Adana is hotter than Samsun and the solar radiation in Adana is higher than in Samsun, the average, the maximum, and the minimum temperatures were in general higher in Adana than in Samsun for the six months.

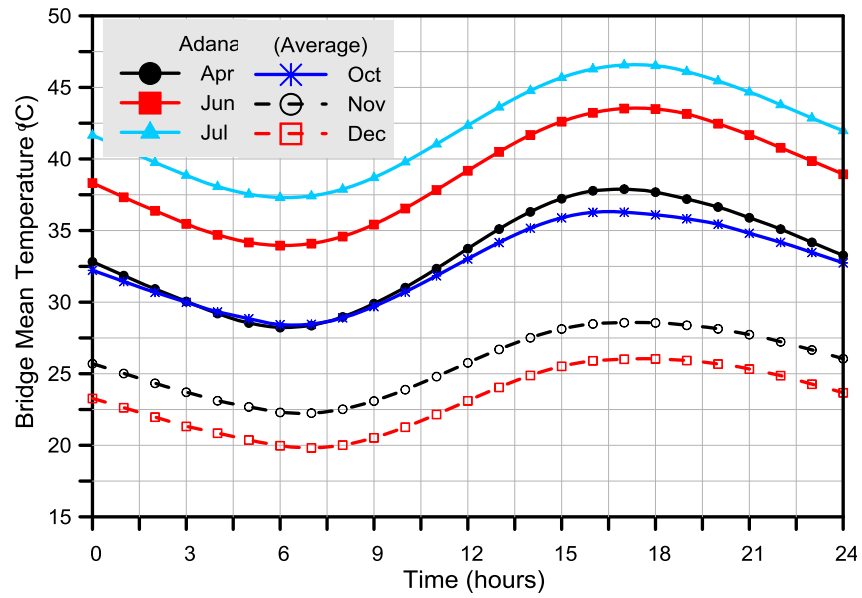


Figure 9.19 Daily variation of the average (mean) bridge temperature for the six months in Adana

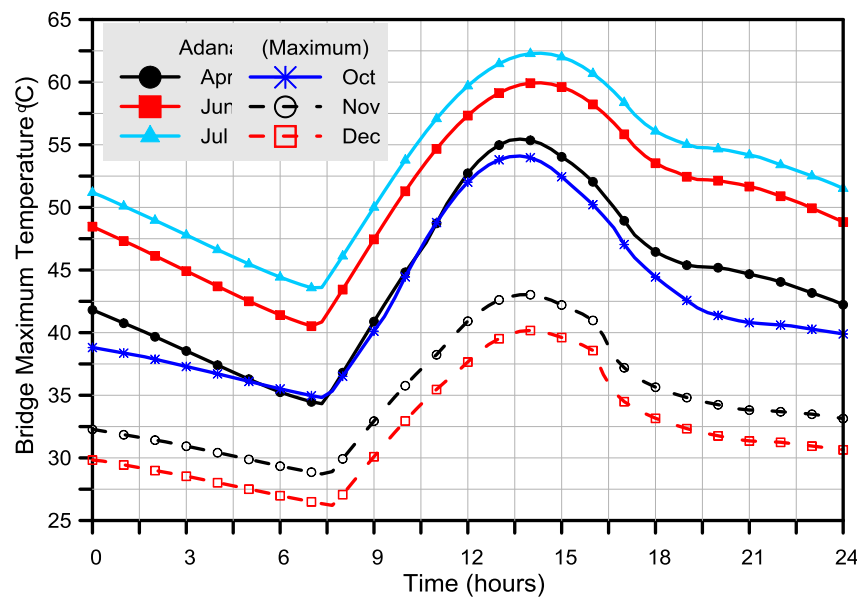


Figure 9.20 Daily variation of the maximum bridge temperature for the six months in Adana

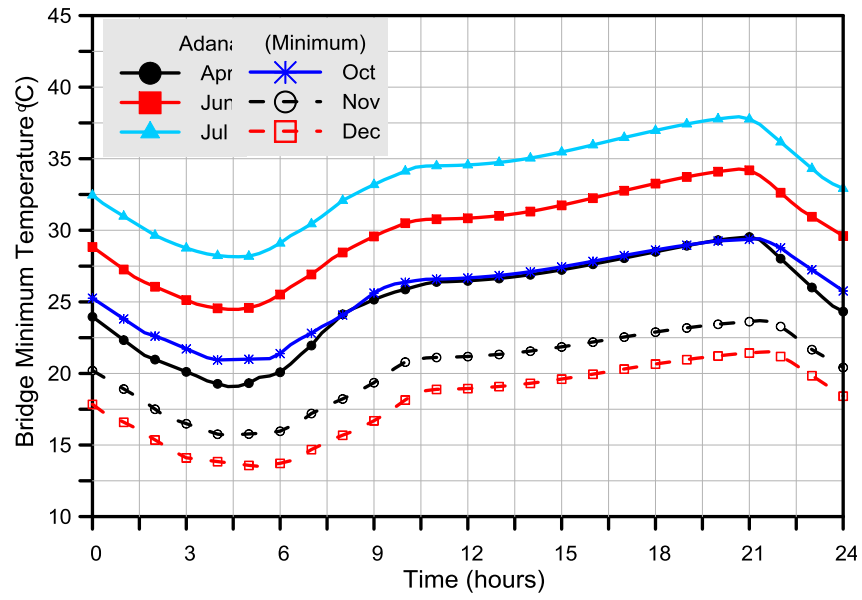


Figure 9.21 Daily variation of the minimum bridge temperature for the six months in Adana

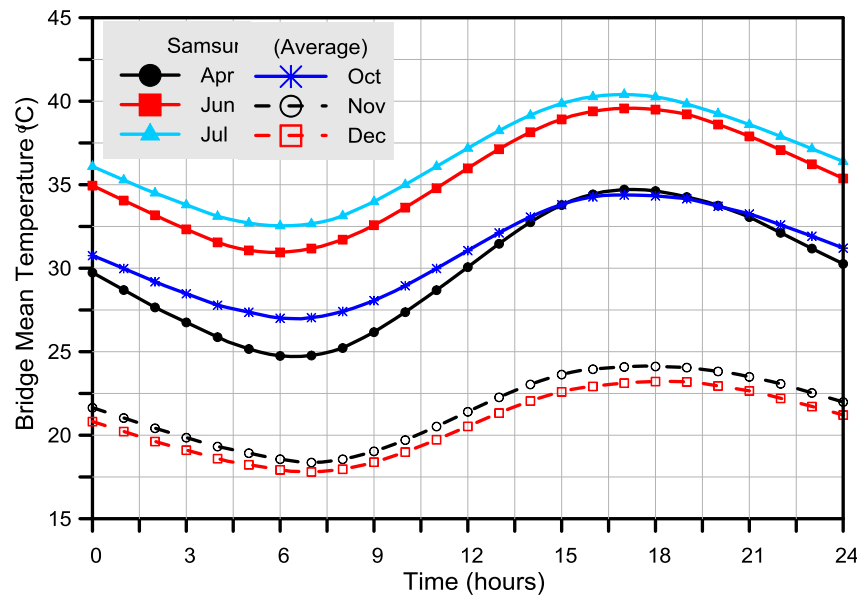


Figure 9.22 Daily variation of the average (mean) bridge temperature for the six months in Samsun

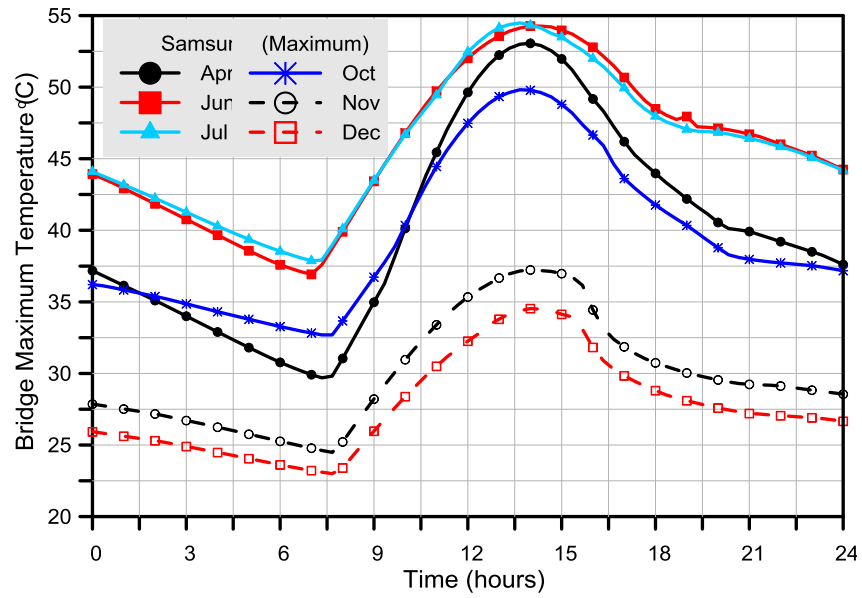


Figure 9.23 Daily variation of the maximum bridge temperature for the six months in Samsun

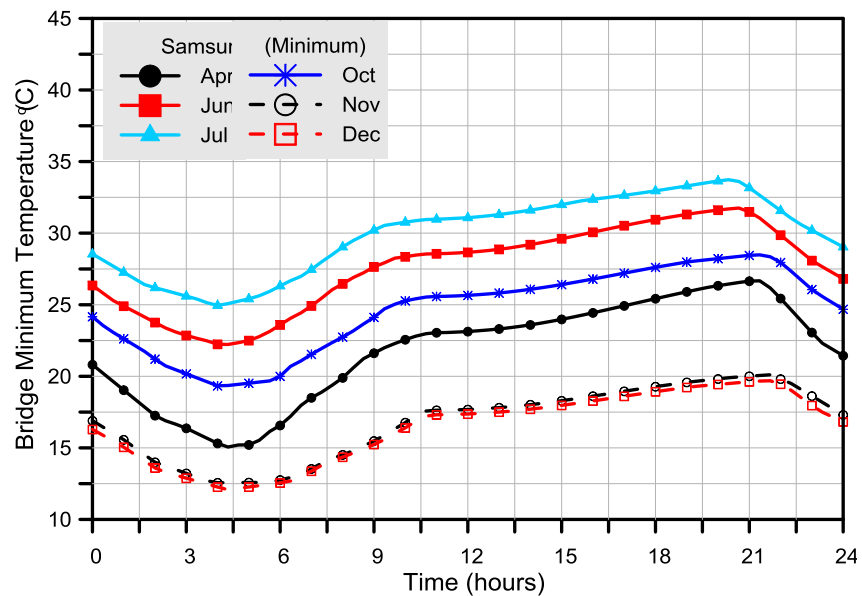


Figure 9.24 Daily variation of the minimum bridge temperature for the six months in Samsun

9.5 Extreme Temperatures and Temperature Gradients in Turkey

In this section, both the positive (heating) and the negative (cooling) temperature gradients, in addition to the bridge's average, maximum, and minimum temperatures were investigated for the selected ten Turkish cities. For the vertical temperature

gradient along the depth of the box girder, the maximum of the gradients along sections A or B was considered. For sections C and D, the maximum temperature gradients of the sections were considered.

9.5.1 Solar Radiation and Air Temperature Distributions in Turkey

To estimate the differences in the expected temperature gradients and bridge temperatures between the different regions of Turkey, the solar radiation and air temperature should be studied for long time. Figures 9.25 and 9.26 show the long-term distributions of the monthly average solar radiation of June and December in Turkey. On the other hand, Figures 9.27 to 9.30 show the long-term distributions of the maximum and minimum air temperatures in June and December.

It is obvious in Figures 9.25 and 9.26 that the south of Turkey suffers much higher solar radiation intensities than the north. On the other hand, the coastal areas along the Black sea, which extend along the north of the Black Sea region and the east of the Marmara region show the lowest solar radiations.

Figure 9.27 shows the distribution of the long-term extreme maximum daily air temperature for the complete Turkish area in June. The figure shows that the maximum air temperatures in summer are also the lowest along the north and the northeast of Turkey, in which the extreme daily maximum temperature was mostly less than 38°C. In addition to these regions, the extreme maximum air temperature was low for the high altitude regions, which are distributed in the different regions of Turkey as shown in Figure 9.27. On the other hand, maximum air temperatures higher than 40°C can be seen along the coastal Mediterranean and Aegean regions, along some of the southern parts of the Black Sea and Marmara regions, and some discrete Anatolian parts. The highest extreme maximum air temperatures were recorded in the Southeastern Anatolian region as shown in Figure 9.27, in which the maximum air temperature exceeded 45°C in June.

Figure 9.28 shows the long-term extreme minimum daily air temperature in June. It is clear that the Southeastern Anatolian region and the coastal areas along the four seas showed the highest minimum air temperatures, while the eastern and central high altitude regions showed the lowest minimum air temperatures. Note that some regions like Çorum in the southern part of the Black Sea region recorded high daily

maximum air temperatures and low daily minimum air temperatures. Thus, it is expected that the daily air temperature difference is high in such regions. Figure 9.29 shows the long-term maximum air temperature distribution of December in Turkey, while Figure 9.30 shows the long-term minimum air temperature distribution of December in Turkey. The figures describe the winter's air temperature distributions in Turkey.

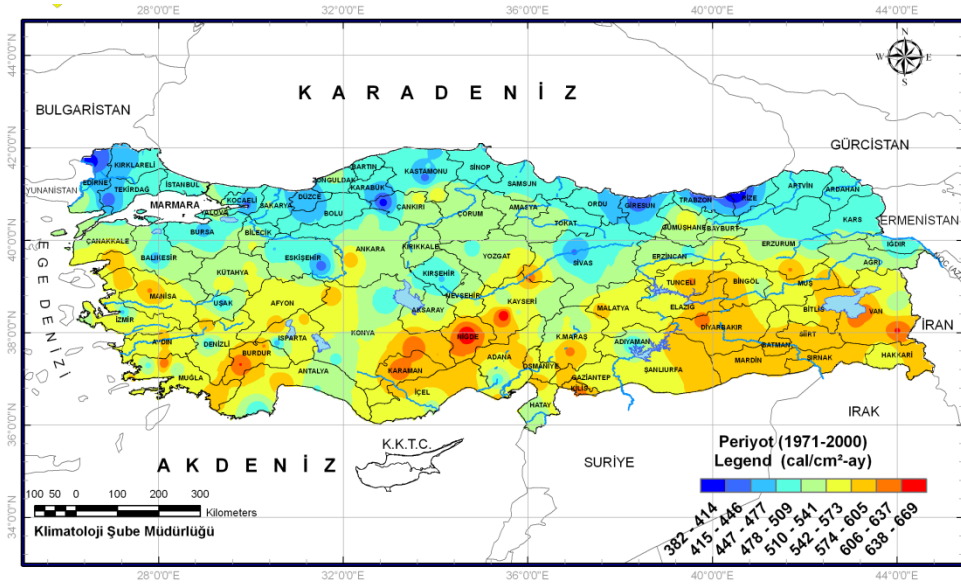


Figure 9.25 The long-term monthly average solar radiation of June in Turkey [92]

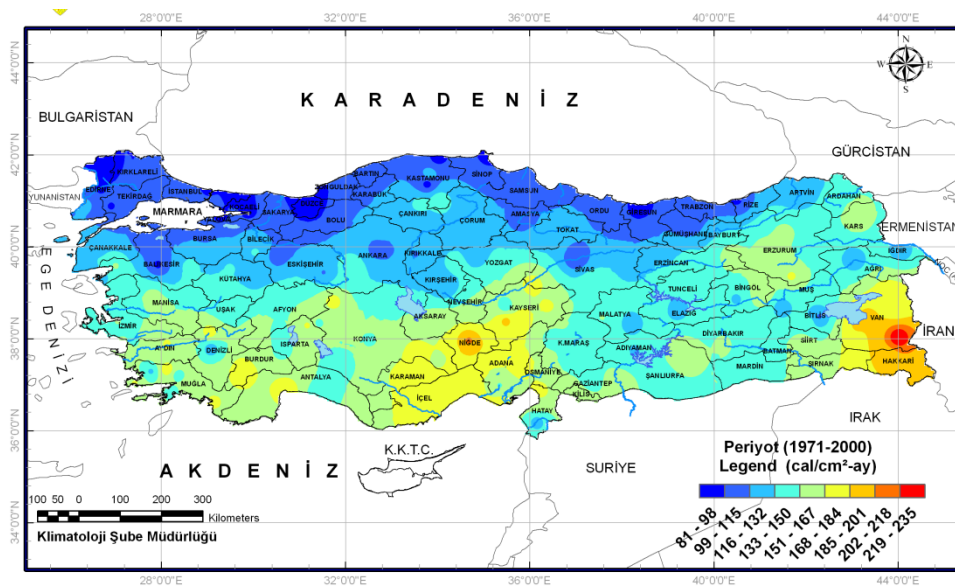


Figure 9.26 The long-term monthly average solar radiation of December in Turkey [92]



Figure 9.27 The long-term maximum air temperature of June in Turkey [92]

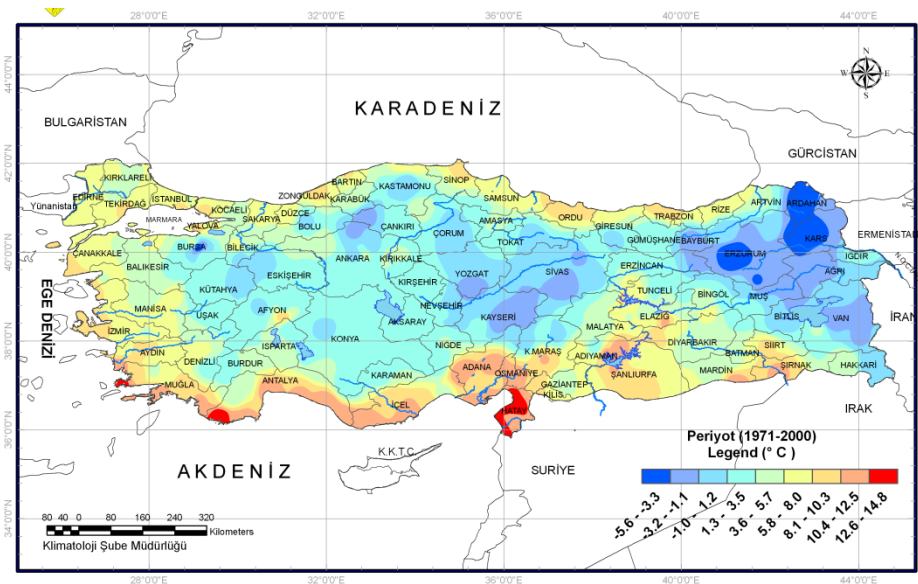


Figure 9.28 The long-term minimum air temperature of June in Turkey [92]

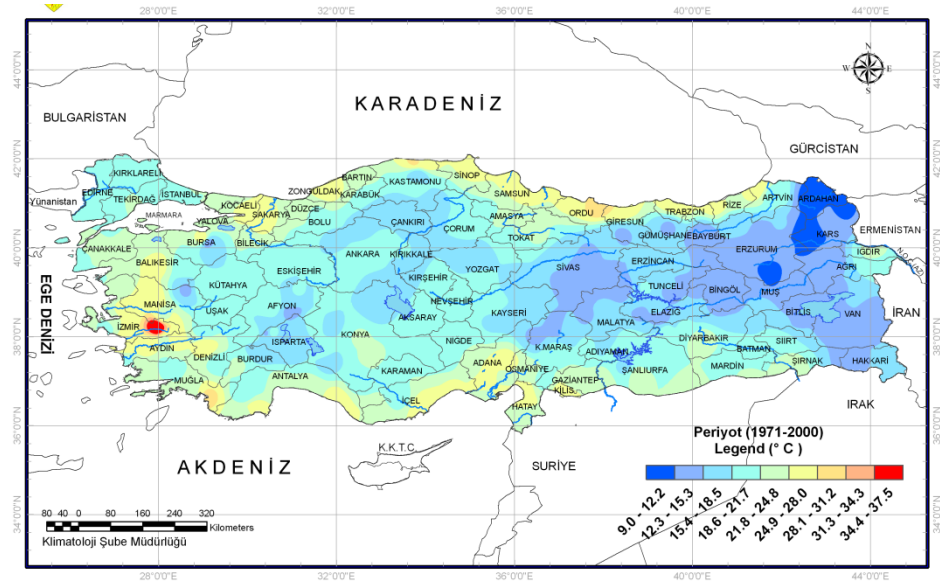


Figure 9.29 The long-term maximum air temperature of December in Turkey [92]



Figure 9.30 The long-term minimum air temperature of December in Turkey [92]

9.5.2 Comparison of the Maximum Vertical Temperature Gradients for the Different Regions of Turkey

Figures 9.31 and 9.32 show the comparisons between the maximum positive and negative vertical temperature gradients along the depth of the box-girder for the ten selected cities. On the other hand, Figures 9.33 through 9.36 show the maximum vertical temperature gradients across the thickness of the top slab (section C) and across the thickness of the bottom slab (section D).

Figure 9.31 shows explicitly that the predicted positive temperature gradients of the ten cities can be divided into two groups, lower than and higher than 23°C. Istanbul and Samsun showed the lowest values of vertical temperature gradients, which were less than or equal to 23°C. Note that both Istanbul and Samsun are located in the zone of low solar radiation discussed in the previous section. The cities that are located in the highest solar radiation zones in Turkey like Antalya recorded high vertical temperature gradients reaching 27°C. Similarly, cities with moderately high solar radiation and high daily air temperature difference like Ankara, Çorum, and Diyarbakir showed vertical temperature gradients higher than 25.5°C.

For the negative temperature gradients shown in Figure 9.32, it is noticed that all cities recorded close top surface gradient values ranging from -7°C to -9°C. It should be mentioned that the maximum gradients were recorded in summer, in which the gradients at the bottom surface were higher than the gradients at the top surface. The negative gradients at the bottom surface ranged from about -10.5°C to -12.0°C. Thus, the negative gradient at the bottom surface is approximately 1.35 to 1.55 times the negative gradient at the top surface. In winter on the other hand, the gradients at the top surface were higher than the gradients at the bottom surface. In addition, the top surface negative gradients were higher in winter than in summer, but only by 1°C to 2°C.

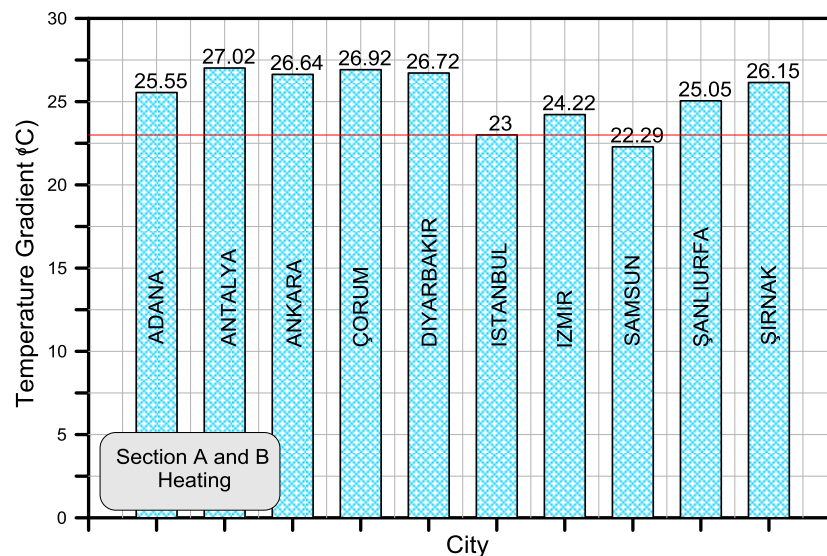


Figure 9.31 Maximum vertical positive temperature gradients (section A or B) for the 10 cities

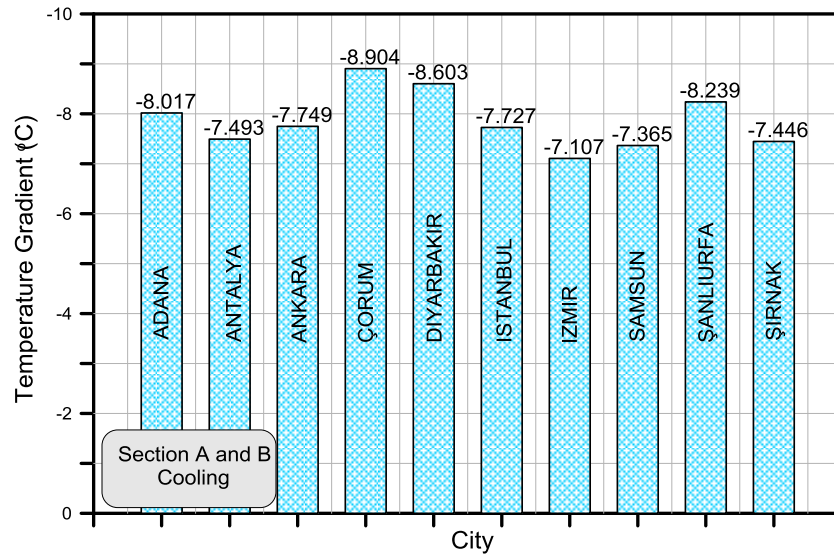


Figure 9.32 Maximum vertical negative temperature gradients (section A or B) for the 10 cities

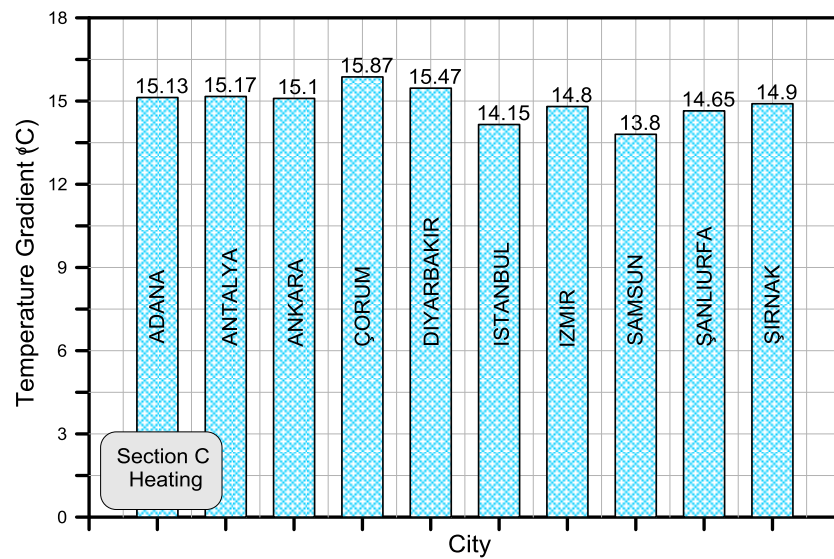


Figure 9.33 Maximum vertical positive temperature gradients across the top slab's middle width-thickness (section C) for the 10 cities

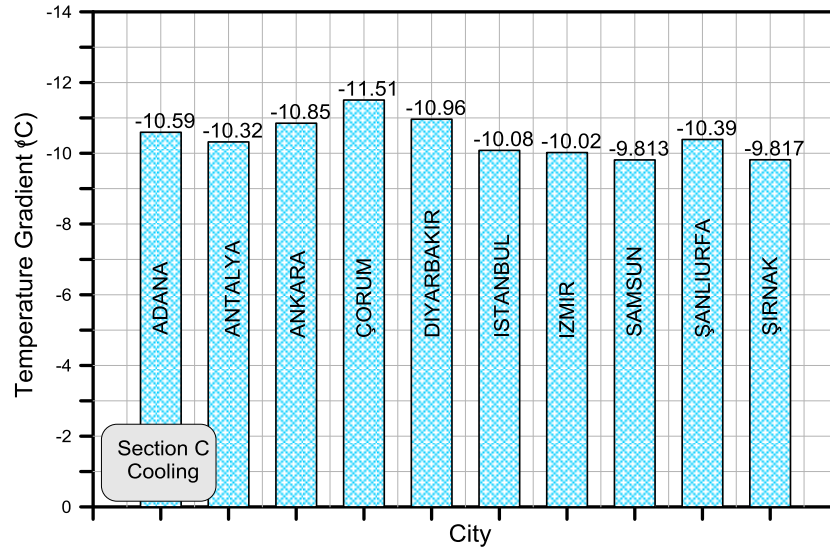


Figure 9.34 Maximum vertical negative temperature gradients across the top slab's middle width-thickness (section C) for the 10 cities

Figures 9.33 and 9.34 show the maximum positive and negative vertical temperature gradients across the thickness of the top slab above the cavity of the box-girder (section C). Figure 9.33 clearly shows that the vertical temperature gradients of Samsun and Istanbul are also the lowest among other cities, while Çorum and Diyarbakir where solar radiation and daily air temperature difference are maximum, showed the largest vertical temperature gradients. Generally, it can be noticed from the comparison between Figure 9.31 and 9.33 that the positive vertical temperature gradient across section C is approximately 0.56 to 0.62 from the positive temperature gradient along section A.

Figure 9.34 shows that the maximum negative temperature gradients of the ten cities range from approximately -9.8°C to approximately -11.5°C . Comparing with Figure 9.32, it is clear that the maximum negative temperature gradient across section C is approximately 1.26 to 1.4 times the maximum negative gradient at the top surface (section A). On the other hand, comparing the negative gradient of section C with the maximum negative gradient of section A but at the bottom surface, the negative gradient along section C is about 0.9 to 0.95 from the maximum gradient at the bottom surface (section A).

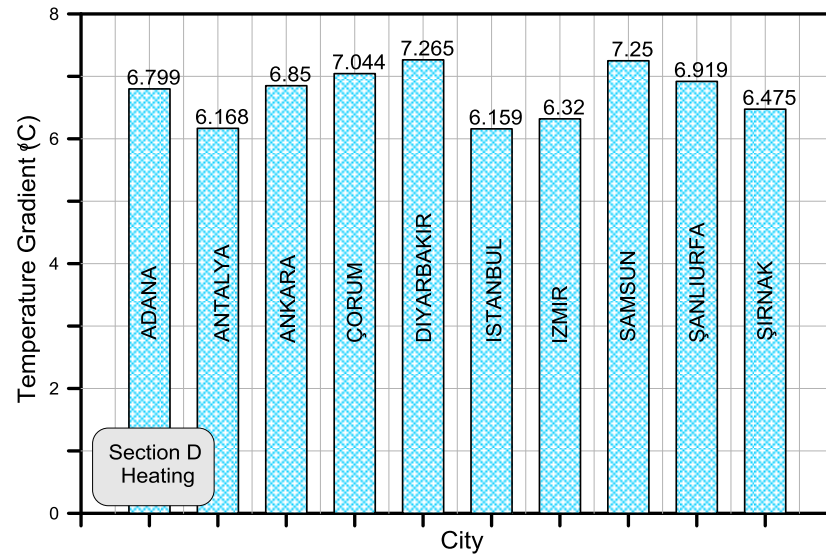


Figure 9.35 Maximum vertical positive temperature gradients across the bottom slab's middle width-thickness (section D) for the 10 cities

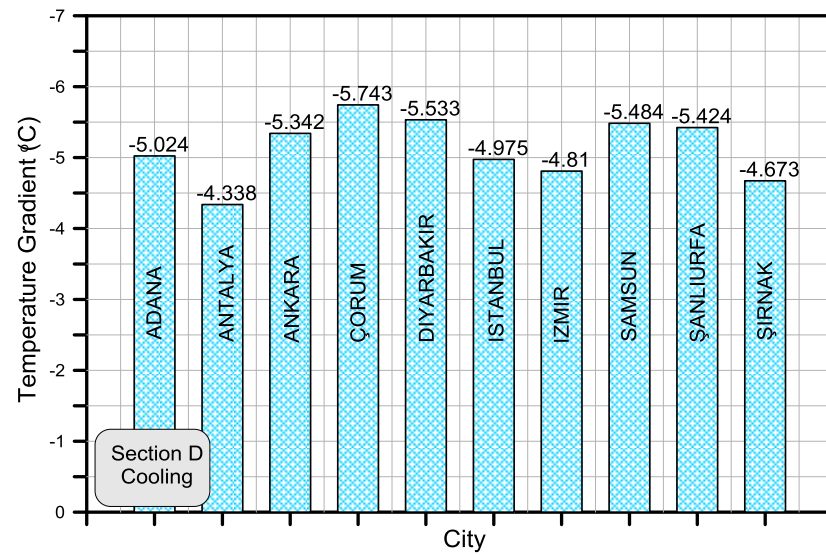


Figure 9.36 Maximum vertical negative temperature gradients across the bottom slab's middle width-thickness (section D) for the 10 cities

The temperature gradients across the thickness of the bottom slab below the box-girder cavity are shown in Figures 9.35 and 9.36 for the heating and cooling cases. Figure 9.35 shows that Samsun and İstanbul still have the lowest value among the ten cities, however, Antalya also shows such a low gradient value compared to its solar radiation incident. Although, all positive gradients across section D are close to

each other with maximum gradient values ranging from approximately 6.2°C to approximately 7.3°C.

Comparing Figure 9.35 with Figure 9.31, it is shown that the maximum positive gradient at the bottom surface of section D is about 0.23 to 0.32 from the maximum top surface positive gradient of section A, while it is about 0.77 to 1.14 times the maximum bottom surface gradient of section A.

Figure 9.36 shows that the negative gradients along section D for the ten cities range from approximately -4.3°C to -5.7°C. Thus, it is about 0.58 to 0.74 from the maximum top surface negative gradient of section A, while it is about 0.37 to 0.53 from the maximum bottom surface negative temperature gradient of section A.

9.6 Proposed Design Temperature Gradient Models for Turkey

In this section, practical temperature gradient models will be derived from the verified finite element model to introduce design provisions for the Turkish standards. These models include positive and negative vertical temperature gradients.

Figure 9.37 shows the distributions of the maximum temperature gradients along the south web for the ten Turkish cities. It is clear in the figure that the variation behavior with depth is the same for all cities in spite of the differences in the temperature values. This behavior similarity is mostly applicable for all other gradient distributions. Therefore, for the design of the temperature gradient distributions, only one city will be presented and compared with. For the other cities, the maximum temperature gradient value will be differed based on the discussion of the previous section. The selected city to derive the gradient models is the country capital Ankara, which is located in the Central Anatolian region.

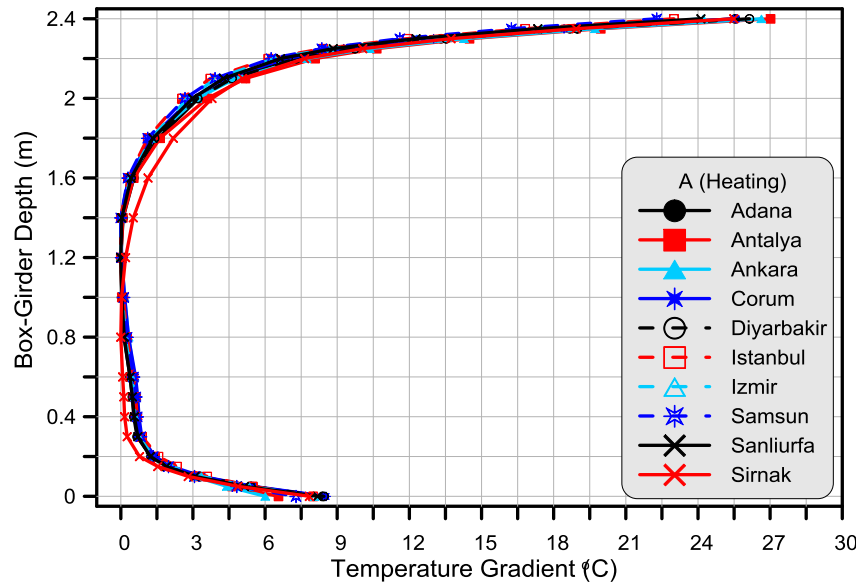
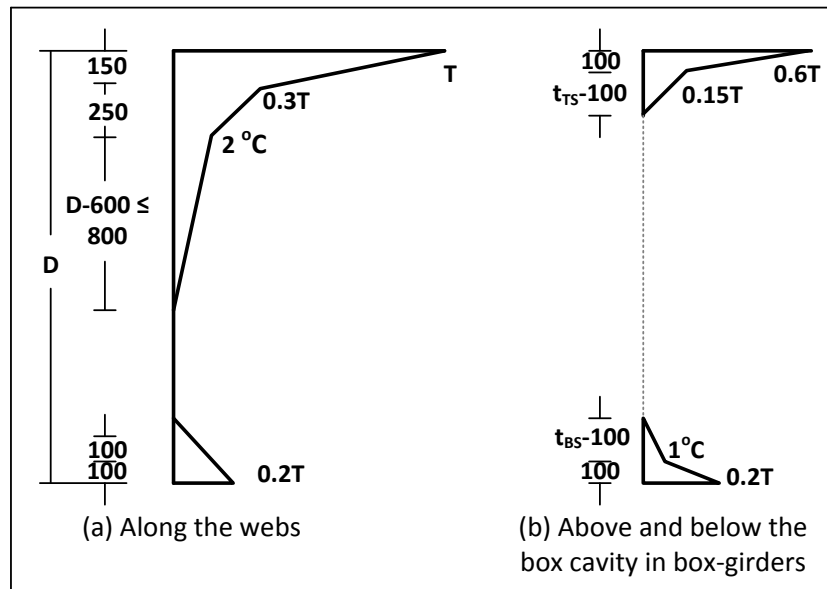


Figure 9.37 Maximum vertical temperature gradient distributions along section A for the 10 cities

Gradient distribution model for the vertical temperature gradients along the depth of superstructure along the webs is proposed and discussed in this section. In addition, vertical gradient models for the temperature gradient distributions across the thickness of the top slab above the box-girder cavity and across the thickness of the bottom slab below the box-girder cavity are proposed and discussed.

9.6.1 Positive Vertical Temperature Gradient Model

The proposed positive vertical temperature gradient distributions are shown in Figure 9.38. As shown in the figure, the proposed gradient composed of two parts. The first part is the model for temperature gradient distribution along the depth of the bridge superstructure, which is shown in Figure 9.38(a). On the other hand, the second part is designed for the temperature gradients across the thickness of the top and bottom slabs of concrete box-girders between the webs, which is shown in Figure 9.38(b).



All dimensions in mm , t_{TS} : thickness of top slab , t_{BS} : thickness of bottom slab or bottom flange , D : depth of the superstructure

Figure 9.38 The proposed positive vertical temperature gradients along the depth of the superstructure and across the thickness of the top and bottom slabs for box-girders

The temperature at any part of the gradient distribution is calculated as a fraction of the maximum top surface temperature, which will be defined based on the location. Along the depth of the superstructure (through the webs), the gradient composes of two parts. The first is a tri-linear distribution along the top 1.2 m. The tri-linear distribution starts at a maximum temperature T at the top surface, then the temperature decreases linearly along the top 0.15 m to a temperature of $0.3T$, from which the temperature decreases down to 2°C along the following 0.25 m, and finally, the third line descends from 2°C to zero at 1.2 m below the top surface. Note that for superstructures shallower than 1.2 m, the depth of the third zone shall be the depth of the superstructure minus 0.6 m.

The second part of the gradient along the depth of the superstructure is the lower part, which is a linear part along the lowest 0.2 m. This part decreases from $0.2T$ at the bottom surface to the zero temperature point at 0.2 m above, as shown in Figure 9.38(a).

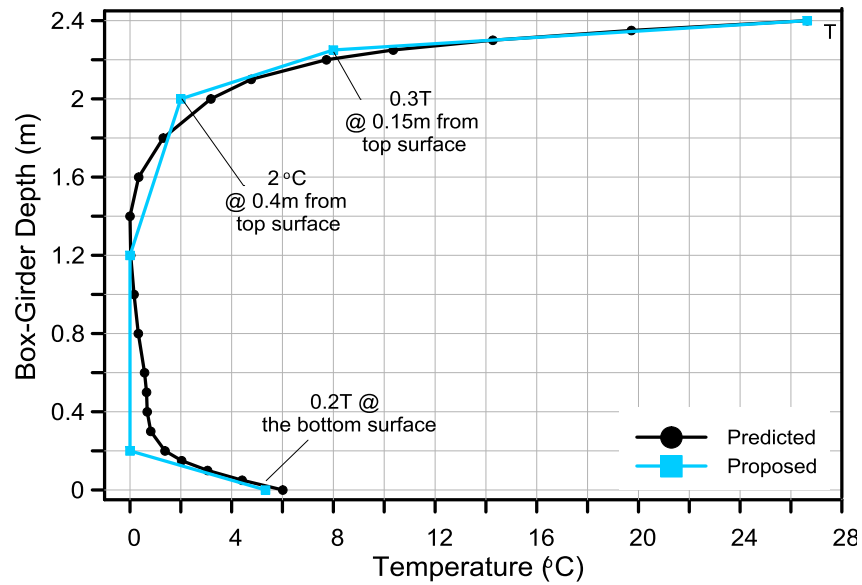


Figure 9.39 Comparison between the predicted and the proposed positive vertical temperature gradient distributions along the depth of the superstructure

Figure 9.39 shows a comparison between the maximum predicted temperature gradient distribution for Ankara in June with the proposed temperature gradient model considering the same temperature at the top surface. As shown in the figure, the error is small between the two distributions. The temperature differences at 0.15 m, 0.4 m, and 1.2 m from the top surface are 2.35°C, 1.18°C, and 0.02°C, respectively. On the other hand, the temperature difference at the bottom surface is 0.67°C, while it is 1.67°C at 0.2 m above the bottom surface.

The gradient model across the top slab is a bilinear that decreases linearly from a surface temperature of $0.6T$ to $0.15T$ at 0.1 m below the top surface, from which the gradient decreases to zero at the bottom interior surface of the top slab as shown in Figure 9.38(b). Similar bilinear model is suggested across the bottom slab but with inversed fashion of decrease (from the bottom exterior surface of the bottom slab to its top interior surface). The temperature gradients at the bottom surface and at 0.1 m above the bottom surface are $0.2T$ and 1°C , respectively as shown in Figure 9.38(b).

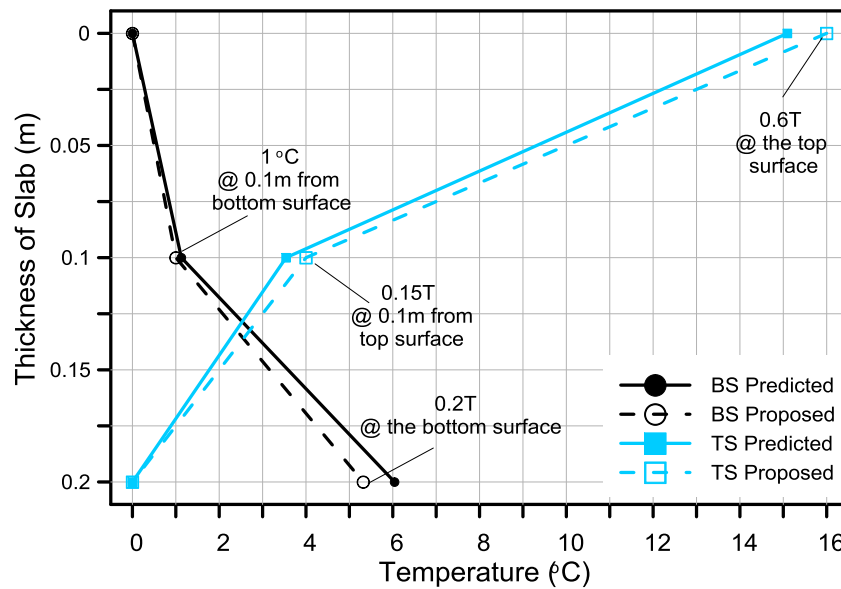


Figure 9.40 Comparison between the predicted and the proposed positive vertical temperature gradient distributions across the thickness of the top and bottom slabs

Figure 9.40 shows a comparison between the proposed distributions for the positive temperature gradient across the thickness of the top and bottom slabs of box-girders with their corresponding predicted maximum gradients. The figure shows that the proposed gradients agree very well with the predicted gradients. The temperature errors between the proposed and the predicted temperature gradient distributions are only 0.9°C and 0.46°C at the top surface and at 0.1 m below the top surface across the top slab, respectively. Moreover, at the bottom surface, the temperature error is 0.72°C , while at 0.1 m above the bottom surface across the bottom slab it is only 0.12°C .

Thus, it can be concluded that for the case of positive vertical temperature gradient distributions along the depth of the bridge superstructure and across the thickness of the slabs above and below the cavity of the box-girder, the temperature errors are generally small between the predicted and the proposed gradient distributions. Thus, the proposed positive vertical temperature gradient model can adequately simulate the real temperature distributions.

9.6.2 Negative Vertical Temperature Gradient Model

The negative gradients and as discussed in section 2.6 in chapter two, are considered for winter or autumn conditions, in which the negative temperature gradient at the top surface is slightly higher than that at the bottom surface. In this section, the negative vertical temperature gradient distribution along the depth of the superstructure is proposed to meet the autumn and winter conditions. However, and as shown in Figures 9.12 and 9.14 for the negative temperature gradient across the top slab, the gradient is much higher in summer than in winter. Similarly, and as shown in Figures 9.16 and 9.18, the negative gradient across the thickness of the bottom slab are much more significant than the corresponding gradients in winter and autumn. Therefore, for the proposed negative gradients across the top and bottom slabs, the summer conditions are considered.

Figure 9.41 shows the proposed negative vertical temperature gradient distributions, both along the depth of concrete superstructures and across the thickness of the top and bottom slabs above and below the box cavity of concrete box-girders. As shown in the figure, all temperatures in the proposed negative vertical gradient models are fractions of the maximum positive temperature gradient at the top surface, which will be specified based on the geographical location.

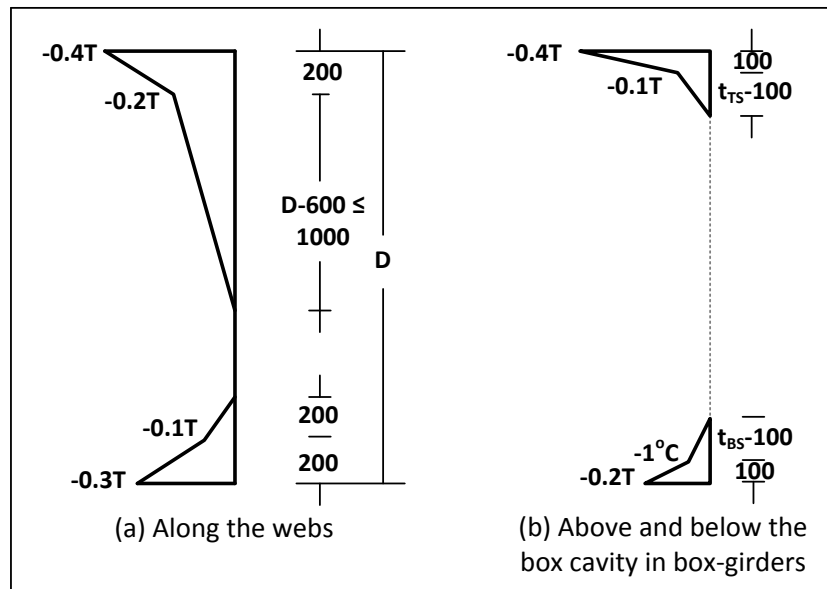
As shown in Figure 9.41, the proposed vertical negative temperature gradient along the depth of concrete superstructure composes of two bilinear distributions. The first simulates the temperature variation along the top 1.2 *m* of the superstructure, while the second simulates the temperature variation along the bottom 0.4 *m* of the superstructure. The maximum top surface and bottom surface temperatures of this model equal -0.4 and -0.3 times the maximum positive temperature gradient at the top surface, while at 0.2 *m* from the top surface and the bottom surface, the proposed temperatures are -0.2 and -0.1 times the maximum positive temperature gradient at the top surface, respectively, as shown in Figure 9.41.

Across the top slab thickness between the webs of box-girders, the proposed negative gradient variation is bilinear. The proposed temperatures at the top surface and at 0.1 *m* below the top surface as fractions of the maximum positive temperature gradient at the top surface are $-0.4T$ and $-0.1T$, respectively. On the other hand, the

proposed temperatures at the bottom surface of the box-girder and at 0.1 *m* above the bottom surface across the bottom slab are $-0.2T$ and -1°C , respectively.

Figure 9.42 shows a comparison between the maximum predicted and the proposed negative vertical temperature gradient distributions along the depth of the superstructure based on Ankara conditions. The Figure shows that the multi-linear proposed negative gradient model simulates the with-depth variation behavior of the predicted temperature gradients. In addition, the temperature errors between the predicted and proposed gradients are minimal, which are in the range of 0.03°C and 1.5°C along the full depth of the box-girder.

Figure 9.43 reveals the high degree of agreement between the maximum predicted and the proposed negative vertical temperature gradient distributions across the top and bottom slabs. The temperature errors are only 0.19°C and 0.1°C at the top surface and at 0.1 *m* below the top surface, respectively, while they are 0.01°C and 0.2°C at the bottom surface and 0.1 *m* above the bottom surface, respectively. Thus, it can be said that the temperature errors are minimal and therefore it can be concluded that the proposed negative temperature gradient model can efficiently simulates the real temperature gradient distribution in the cooling case.



All dimensions in mm , t_{TS} : thickness of top slab , t_{BS} : thickness of bottom slab or bottom flange , D : depth of the superstructure

Figure 9.41 The proposed negative vertical temperature gradients along the depth of the superstructure and across the thickness of the top and bottom slabs for box-girders

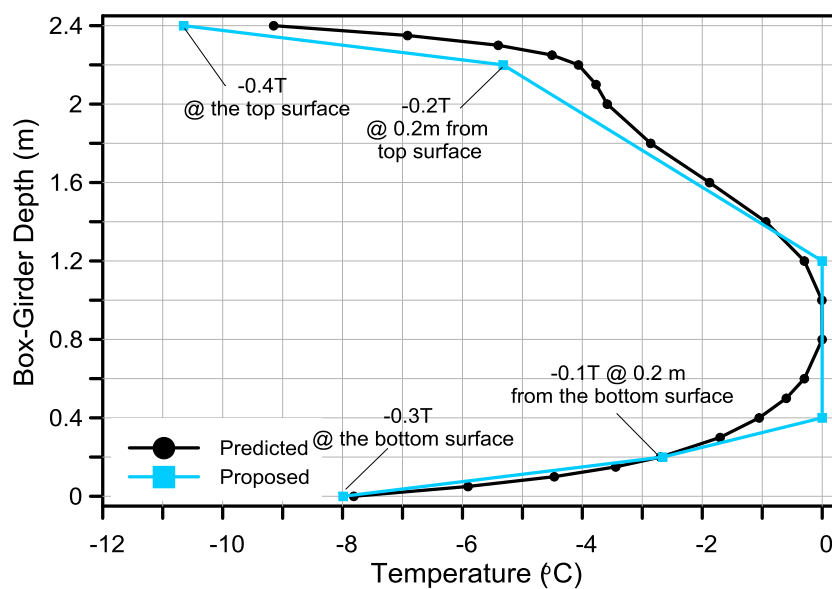


Figure 9.42 Comparison between the predicted and the proposed negative vertical temperature gradient distributions along the depth of the superstructure

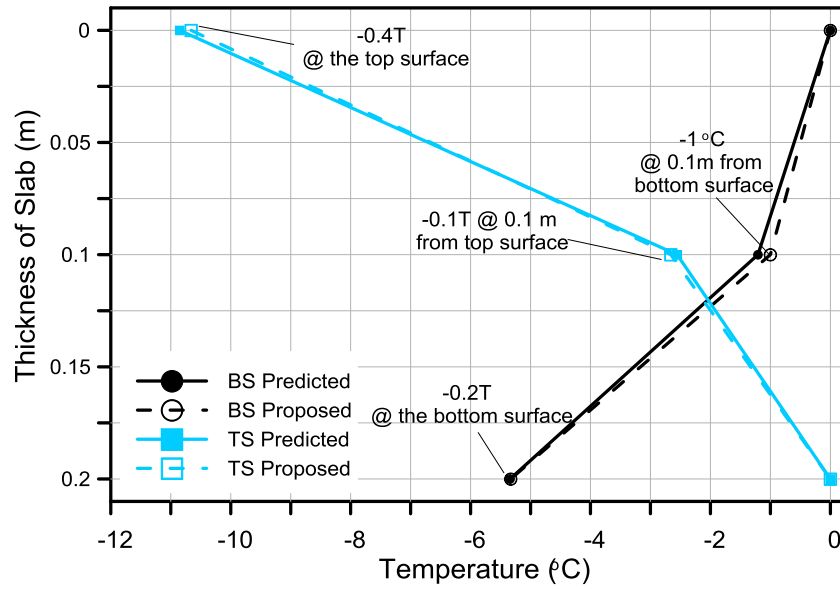


Figure 9.43 Comparison between the predicted and the proposed negative vertical temperature gradient distributions across the thickness of the top and bottom slabs

9.6.3 The Maximum Temperature Gradient T

As discussed in chapter 5 and as shown in Figure 5.1, the daily maximum temperature gradient at the top surface T is correlated to high degree with the daily total solar radiation. However, and as shown in Equation 5.5, the difference between the daily maximum and minimum of air temperature is also an effective factor.

As discussed in section 9.5.1, the coastal regions around the black sea show low intensities of solar radiations during the hot and the cold seasons. In addition, the daily maximum air temperature is low for these regions, while the daily minimum air temperature is moderately high compared to the other regions. Thus, the daily temperature difference is also low for this region.

Figure 9.44 shows the long term annual total solar radiation of Turkey, in which it is clear that the northern parts of the Black Sea region and the Eastern parts of the Marmara region (the coastal areas of the black sea) show lower solar intensities than the southern and middle parts of Turkey. The total annual solar radiation of the northern region is generally lower than 1350 kWh/m^2 , while it ranges from 1500 to more than 1700 kWh/m^2 on the southern regions.

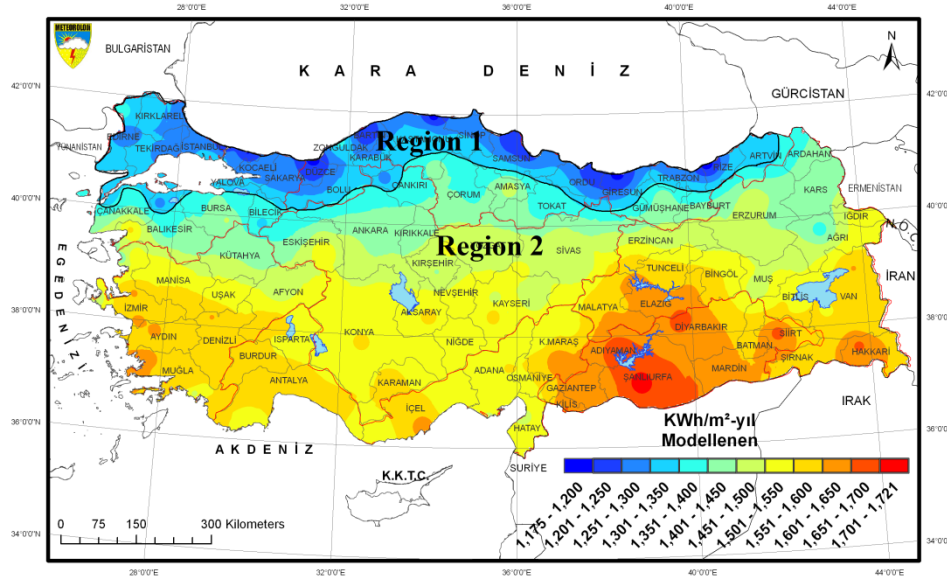


Figure 9.44 The long-term annual total solar radiation in Turkey [92]

Thus, it can be concluded from the discussion in section 9.5.2 and from the observation of Figure 9.31 in combination with Figure 9.44 that for the positive vertical temperature gradients, Turkey can be divided into two regions. The first is the northern area along the coast of the Black Sea, which includes the northern parts of the Black Sea region and the eastern parts of Marmara region and termed as Region 1. The maximum temperature gradient of this region can be taken as 26°C , which is the recorded maximum temperature gradients plus 3°C as a safety factor. The second region includes the rest of the Turkish area and termed as Region 2, with maximum gradient of 30°C , including the safety factor for extreme conditions.

9.6.4 Adjustments to the Maximum Temperature Gradient T

The results of the geometrical parametric studies of chapter seven showed that some parameters have significant influence on the vertical temperature gradients along the depth of concrete superstructure. Based on the results of chapter 7, the following adjustments are suggested for positive gradient model only (not applicable for negative gradient):

1- For deep superstructures, with overall depth exceeding 10 m , the top tri-linear part of the positive gradient shall be considered along the top 1.5 m , instead of the top 1.2 m . Thus, the depth of the third linear part shall be 1.1 m instead of 0.8 m .

2- The temperature effects shall be calculated for the unsurfaced case during the construction, and the surfaced case along the bridge life span. For surfaces topped with asphalt layers, the adjustments listed in Table 9.8 shall be multiplied by the temperature gradient T and applied to the proposed positive gradient model. Linear interpolation and extrapolation shall be allowed for topping thicknesses other than those listed in Table 9.8.

Table 9.8 Adjustment to the temperature gradient T for different topping thicknesses

Thickness of Topping Layer	Adjustment Factor
No topping layer	None
50 mm	1.3
100 mm	1.0
150 mm	0.8
200 mm	0.65

9.7 Proposed Design Bridge Mean Temperatures for Turkey

Figure 9.45 shows the long-term recorded extreme maximum air temperature for Turkey, while Figure 9.46 shows the long-term recorded extreme minimum air temperatures for Turkey, which were both prepared based on record data of 30 years, from 1971 to 2000. Equation 5.19 can be used together with the extreme daily maximum from Figure 9.45 to estimate the maximum mean temperature of concrete bridge superstructures (MT_{max}). Similarly, Equation 9.20 can be used with the extreme daily minimum temperature contour map of Turkey, which is shown in Figure 9.46 to estimate the minimum mean temperature of concrete bridge superstructures (MT_{min}). Equations 5.19 and 5.20 can be simplified for practical use to Equations 9.1 and 9.2.

$$MT_{max} = 1.1T_{max} \quad (9.1)$$

$$MT_{min} = 1.1T_{min} + 6 \quad (9.2)$$

The higher temperature shall be considered from the temperature ranges given in Figure 9.45 to estimate the maximum air temperature (T_{max}), while the lower temperature shall be considered from temperature ranges given in Figure 9.46 to estimate the minimum air temperature (T_{min}). The reference temperature, to which

the maximum expansion (ΔL_+) and maximum contraction (ΔL_-) shall be evaluated is the mean temperature of the bridge superstructure at the time of the final erection on supports (T_o). Thus, the design expansion and contraction shall be evaluated using Equations 9.3 and 9.4, respectively.

$$\Delta L_+ = \alpha L(MT_{max} - T_o) \quad (9.3)$$

$$\Delta L_- = \alpha L(MT_{min} - T_o) \quad (9.4)$$



Figure 9.45 The long-term extreme maximum air temperature in Turkey [92]

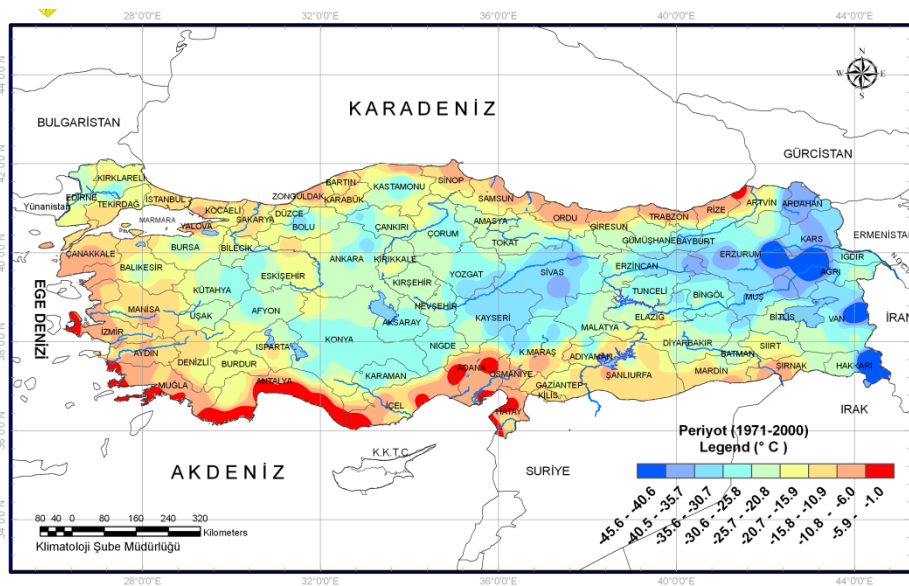


Figure 9.46 The long-term extreme minimum air temperature in Turkey [92]

9.7.1 Design Example

If the estimated mean temperature of a concrete bridge superstructure constructed in Gaziantep is 15°C. Then the design maximum expansion and contraction shall be calculated as follows:

1- From Figure 9.67, the maximum air temperature is 45°C (third zone from right), while from Figure 9.68, the minimum air temperature is -20.7°C (fourth zone from the right).

2- Using Equation 9.1 and 9.2, the bridge maximum and minimum mean temperatures are:

$$MT_{max} = 1.1T_{max} = 1.1(45) = 50^{\circ}\text{C}$$

$$MT_{min} = 1.1T_{min} + 6 = 1.1(-20.7) + 6 = -17$$

3- Then, the design expansion shall be calculated using Equation 9.3, while the design contraction shall be calculated using Equations 9.4, and as follows:

$$\Delta L_{+} = \alpha L(MT_{max} - T_o) = \alpha L(50 - 15) = 35\alpha L$$

$$\Delta L_{-} = \alpha L(MT_{min} - T_o) = \alpha L(-17 - 15) = -32\alpha L$$

CHAPTER TEN

FINITE ELEMENT STRUCTURAL ANALYSIS OF BOX-GIRDER BRIDGES

10.1 General

The formation of thermal stresses along the vertical and transverse directions of the cross-section depends on the temperature distributions along these directions. If the temperature distribution is linear, no stresses are formed, while thermal stresses are formed due to nonlinear temperature distribution. In this case, the free strain is nonlinear; however, each fiber is restricted by the adjacent fibers, and hence cannot expand or contract freely. Under the consideration of the Navier's hypothesis, plane sections should remain plane and perpendicular to neutral axis after deformation, which means that the actual thermal strain should be linear. The difference between the free and the actual strain distributions results in the stresses that restrain the free nonlinear thermal deformation, these stresses are called as self-equilibrating stresses.

In this chapter, the experimental box-girder segment is analyzed for thermal stresses and movements using the COMSOL finite element package.

10.2 Background of Thermal Stresses

Considering the box-girder shown in Figure 10.1, the section is constant along the straight span along y-axis, hence, temperature is not variable from section to another along the y-axis. The temperature difference is then a function of the vertical (z) and the transverse (x) coordinates from the centroid of the section. Thus, the temperature difference of a point with coordinates x and z is $T(x, z)$.

The free strain, which is related to the real nonlinear temperature difference $T(x, z)$ is:

$$\epsilon_T = \alpha T(x, z) \quad (10.1)$$

where α is the coefficient of thermal expansion of the concrete.

If ϵ_o is the axial strain that occurs at the center of gravity due to the temperature difference $T(x, z)$, ρ_z is the radius of curvature in the vertical z -direction at the centroid of the section due to the temperature difference $T(x, z)$, and ρ_x is the radius of curvature in the transverse x -direction at the centroid of the section due to the temperature difference $T(x, z)$. Then the total longitudinal thermal stress that occurs from the temperature difference $T(x, z)$ at any point (x, z) is:

$$\sigma_y = -E\epsilon_T + E\epsilon_o + E \frac{z}{\rho_z} + E \frac{x}{\rho_x} \quad (10.2)$$

where E is the modulus of elasticity of the isotropic material.

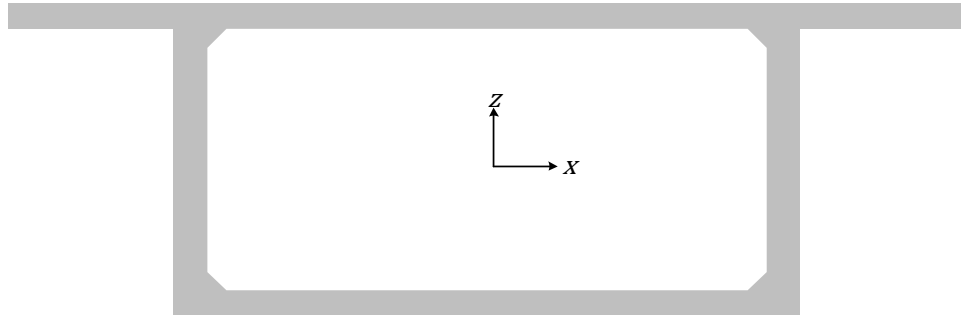


Figure 10.1 Coordinate system of the experimental box-girder

The free strain ϵ_T is artificially restricted to occur freely by the adjacent fibers, causing an artificially restrained stress equals:

$$\sigma_T = E\epsilon_T \quad (10.3)$$

To remove the artificial restraints, this restrained stress can be presented as an axial force P and bending moments M_z and M_x , where:

$$P = \int_A \sigma_T dA = \int_A E\alpha T(x, z) dA \quad (10.4)$$

$$M_z = \int_A \sigma_T x dA = \int_A E\alpha T(x, z) x dA \quad (10.5)$$

$$M_x = \int_A \sigma_T z dA = \int_A E\alpha T(x, z) z dA \quad (10.6)$$

If the moments of inertia of the cross section about z and x axes are:

$$I_z = \int_A x^2 dA \quad (10.7)$$

$$I_x = \int_A z^2 dA \quad (10.8)$$

Then the axial strain ϵ_o and the radii of curvature ρ_z in z direction and ρ_x in x direction can be represented as:

$$\epsilon_o = \frac{P}{AE} \quad (10.9)$$

$$\frac{1}{\rho_z} = \frac{M_x}{EI_x} \quad (10.10)$$

$$\frac{1}{\rho_x} = \frac{M_z}{EI_z} \quad (10.11)$$

This means that the total longitudinal thermal stress in Equation (10.2) can be re-written as:

$$\sigma_y = -E\alpha T(x, z) + \frac{P}{A} + \frac{M_x}{I_x} z + \frac{M_z}{I_z} x \quad (10.12)$$

10.3 The 3D Finite Element Box-Girder Bridge

Considering the experimental box-girder segment explained in chapter 3, which has the cross section details shown in Figure 3.2, a 3D finite element analysis was carried out in this study to solve for temperature and their structural effects including displacements and stresses. The 3D finite element structural analysis of a box-girder bridge with span of 50 m was conducted using COMSOL Multiphysics [23] by the coupling of the solid mechanic interface and the heat transfer interface. Figure 10.2 shows the 3D geometry of the analyzed box-girder.

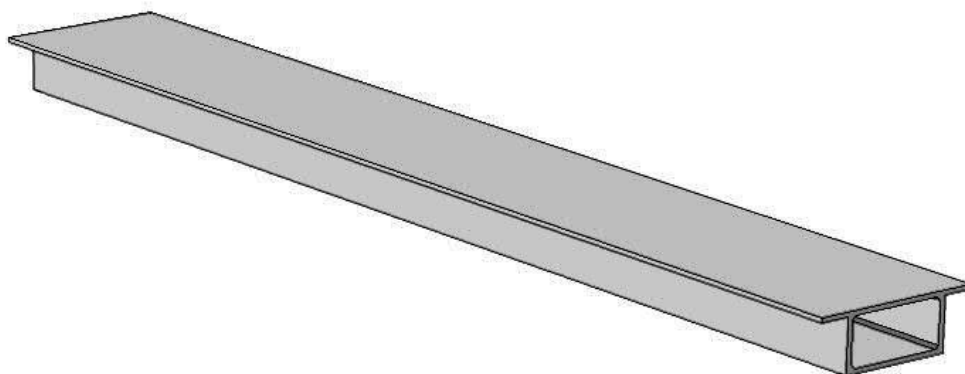


Figure 10.2 The 3D finite element model of the analyzed box-girder

10.3.1 The Finite Element Analysis

As reviewed in sections 2.4 and 2.7 in chapter two, the followed procedure of all of the reviewed previous works is to analyze the thermo-structural behavior in two subsequent steps. First, a heat transfer model is conducted to evaluate the temperature distribution at different time steps. This analysis is mostly a simplified 2D, which includes the solar radiation and the surface-to-ambient radiation implicitly as an equivalent linear convection load, instead of calculating for the surface radiosity at each time step. The second step of the analysis is the applying of the maximum gained vertical and lateral temperature gradients to a solid mechanics finite element model to evaluate the thermal movements and thermal stresses.

In the current study, the heat transfer with surface-to-surface radiation module is coupled with the solid mechanics module forming the thermal stress interface. The used coupled thermal stress module calculates for three dependent variables (five degree of freedom) simultaneously at each time step. The dependent variables are the temperature (T), the surface radiosity (J), and the displacement field (U). The goal of this coupled finite element analysis is to calculate the displacement field (U), which represents the displacements (u, v, w) in the local directions (x, y, z) and the global directions (X, Y, Z). From the displacement field, the stresses, the internal forces, and the reactions are calculated.

10.3.2 The Boundary Conditions

The simply supported case was considered to calculate for the vertical, the lateral, and the longitudinal movements in addition to the normal self-equilibrating stresses resulted from the nonlinear temperature distributions. The bridge was assumed to set on two rectangular bearing pads at each of the two end supports.

From one side of the span, the bearing pads were designed to prevent the vertical, the lateral, and the longitudinal movements. As shown in Figure 10.1, the plane of the cross-section is the x-z plane, which means that the longitudinal axis is the y-axis. Thus, the boundary conditions at this end are:

$$u_{y=0} = 0, v_{y=0} = 0, w_{y=0} = 0 \quad (10.13)$$

From the opposite side of the span, the bearing pads were designed to prevent the vertical and lateral movements, while it allows for longitudinal movement. Thus, the boundary conditions at this end are:

$$u_{y=50} = 0, w_{y=50} = 0 \quad (10.14)$$

10.3.3 The Discretization of the Finite Element Model

Solid elements were used to mesh the body of the bridge to calculate for both temperature and displacement fields, while fictitious triangular surface elements were used to evaluate the surface-to-ambient and surface-to-surface radiations. For both the temperature field and the displacement field, second-order (quadratic) tetrahedral elements were used to increase the accuracy of the solution. Figure 10.3 shows the finite element mesh of the box-girder bridge model.

Linear elements were used for the radiosity (J), which as discussed in chapter six, are sufficient and recommended by COMSOL. To assure high accuracy, the hemicube method was used to calculate the view factors. As discussed in chapter six, the radiosity calculations are the most complicated part of the analysis and it magnifies the solution time significantly, therefore, linear elements were used and the surfaces were collected in groups to reduce the solution time.



Figure 10.3 The mesh of the finite element box-girder bridge

10.3.4 Initial Conditions and Material Properties

The initial temperature was considered equal to the temperature of the ambient air at the start time of the analysis. The analysis was started 72 hours before the target day. Therefore, the air temperature at the mid night, three days before the target day was used as the initial temperature of the analysis. In addition, this temperature was considered as the strain reference temperature, to which all strains are compared. On the other hand, The initial displacements were taken as zero at the start time of the analysis, thus:

$$u_o = 0, v_o = 0, w_o = 0 \quad (10.15)$$

Linear elastic material properties were considered for the used concrete. The thermal properties and the density of the used concrete were considered as described in section 6.3.4 in chapter six.

The AASHTO LRFD [12], specified that the coefficient of linear thermal expansion (α) for normal weight concrete ranges from $5.4 \times 10^{-6} / ^\circ\text{C}$ to $13.4 \times 10^{-6} / ^\circ\text{C}$. In

this study, the coefficient of thermal expansion was taken as $10 \times 10^{-6} / ^\circ\text{C}$, while the Poisson ratio (ν) was considered as 0.2.

As recorded in section 3.6 in chapter three, the tested compressive strength of the standard ASTM cylinders was 28.9 *MPa*, and according to section 8.5.1 of the ACI 318-11 [93], the modulus of elasticity of concrete can be evaluated by:

$$E = 4700\sqrt{f'_c} \quad (10.16)$$

Thus, the resulted modulus of elasticity of the used concrete in the experimental box-girder, which is used in the finite element analysis of this chapter is 25 *GPa*.

10.4 The Thermal Response Results

The finite element thermal stress analysis was conducted for three days. These are the days used for the verification of the thermal model in chapter six, which are 10-July-2013, 22-December-2013, and 14-June-2014.

In this chapter, the stresses and displacements are visualized and discussed at the exterior surface points a to f, the interior surface points g to l, in addition to the interior points C_{TS} , C_{BS} , C_{SW} , and C_{NW} for the 24 hours of the selected days. Moreover, the stresses and displacements at specific time steps are visualized and discussed along sections A to D. Sections A and B pass vertically through the centerlines of the south and north webs, while sections C and D extend laterally through the centerlines of the top and bottom slabs. Figure 10.4 shows the points and sections at and along which the stresses and displacements are investigated.

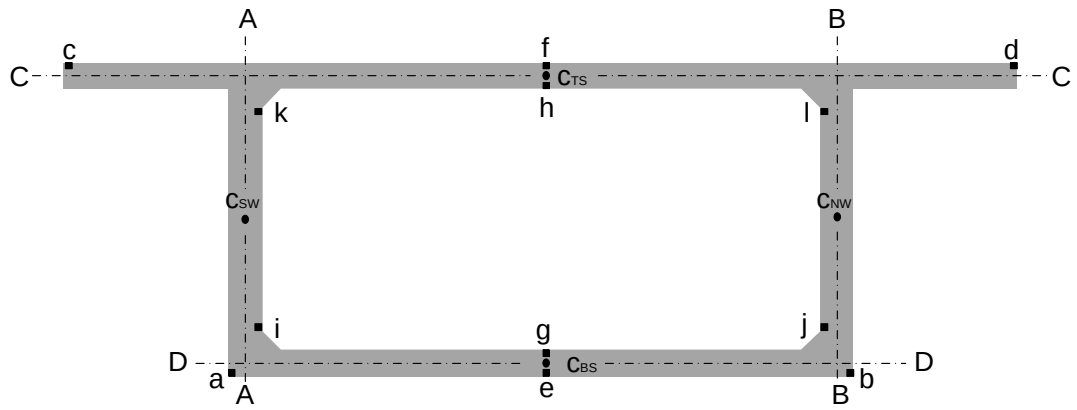


Figure 10.4 The sections and the points of the studied stresses and deformations

10.4.1 Thermal Stresses

At the early afternoon of a hot summer day, the temperature gradient distribution would be nonlinear as shown in Figure 10.5(a). Such a temperature distribution produces a nonlinear free thermal strain according to Equation 10.1, while because plane sections should remain plane after deformation, the actual strain should be linear as represented by the shaded area in Figure 10.5(b). The restricted strain, which is represented by the difference between the free nonlinear strain and the actual linear strain, would results in the self-equilibrating stress distribution shown in Figure 10.5(c), in which the top and the bottom regions are under compression (-ve), while the mid-height region is under tension (+ve).

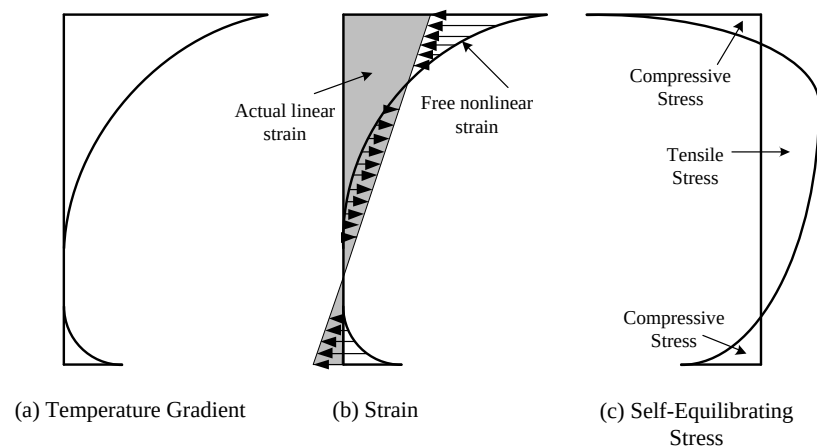


Figure 10.5 Strain and Stress distributions due to nonlinear temperature gradient

10.4.1.1 Thermal Stress Variation at the Surface Points during the 24 Hours

Figures 10.6 through 10.11 show the normal stress variation along the 24 hours of the presented days (10-July, 22-December, and 14-June) at the surface points shown in Figure 10.4.

Figure 10.6 shows the stress variations of the corner points on the top and the bottom surfaces of the box girder in 10-July-2013. The figure shows that in general the stress at these points is tensile during the night and the early morning hours. Because of the absence of solar radiation and the low air temperatures during these hours, the exterior surfaces are subjected to the cooling phase of convection and re-radiation, while during the daytime, the solar radiation increases gradually. Thus, warming the ambient air temperature and causing a global increase in the temperature of the exposed surfaces, which reverse the stresses from tensile to compressive. The maximum tensile stress was recorded at point d, which was 2.78 *MPa*, while the maximum compressive stress was recorded at point c and was -2.62 *MPa*.

Figure 10.7 shows the stress variation at the points e, f, g, and h in 10-July. Points e and f, which are exterior points showed similar behavior to those shown in Figure 10.6, while the interior points g and h showed an inverse behavior, where tensile stresses increased as heating from the top surface increased. This is an expected result, because the cooling of the top surface during the cold night hours reverses the temperature gradient from positive to negative, which in turn reverses the stress sign. The maximum tensile and compressive stresses of this group of points were recorded at point f (at the center of the top surface), which were 1.81 *MPa* and -2.79 *MPa*, respectively.

Figure 10.8 shows the stress variations at the interior points i, j, k, and l in 10-July. The figure shows that these points showed similar behavior to that of the interior points g and h but with time delays that shifted the inflection points and the points of maxima by about 2 hours. The points g and h are the interior surface points of the top and the bottom slabs, where heating from solar radiation and reflected radiation occurs directly with sunrise and reaches these surfaces quickly. On the other hand, the points i, j, k, and l are located at the interior surfaces of the webs, which are

subjected to lower solar and reflected radiations during summer and are thicker than slabs. Thus, heat reaches these points slower than points g and h, which causes time delays for the extreme points of the curves.

Figures 10.9 to 10.11 show the stress distributions at the selected points in 22-December-2013. Figure 10.9 shows the same stress variation behavior as in Figure 10.6, but the inflection points are shifted about 3 to 4 hours (later in morning and earlier in evening) because of the different times of sunrise and sunset between summer and winter.

The maximum recorded compressive stress was recorded at point a, which was -3.83 MPa , while the maximum tensile stress was 1.0 MPa , which was recorded at point b. Notice that the stresses at point a represent the resultant of the stresses that are caused by the vertical temperature gradient along the depth of the box-girder through the web and the lateral temperature gradient along the width of the bottom slab. This resultant is higher in 22-December than in 10-July or in 14-June because of the high lateral temperature gradient (19°C) and moderately high vertical temperature gradient (11°C). The experimentally recorded maximum vertical and lateral gradients are recorded in Table 4.1 in chapter 4.

The behaviors of the stresses at points e to h shown in Figure 10.10 are the same as their corresponding points in Figure 10.7 considering the time shifts due to the difference of the times of sunrise and sunset between 10-July and 22-December.

What was discussed for points i, j, k, and l in Figure 10.8 is applicable in Figure 10.11. However, the stress at point i is interesting. In summer, the sun is high in the sky during the mid-day hours and the bottom half of the south web (point i) is mostly shaded. During the hours close to the sunrise and sunset, the sun strikes the north web while the south web is completely shaded. Thus, the bottom region of the south web is kept shaded along the day, and hence tensile thermal stresses occur along most of the day as shown in Figure 10.8. In December, on the other hand, the south web is subjected to low angle sunrays along the full day hours. Thus, the stress is compressive almost along the full day as shown in Figure 10.11. The stress of point i in 22-December-2013 ranged between -0.06 MPa and -1.2 MPa .

The Figures from 10.12 to 10.14 show the stress variation at the selected exterior and interior surface points in the summer of 2014 in 14-July. Comparing these figures with their corresponding figures in 10-July-2013 (Figures 10.6 to 10.9), the behaviors are the same and the stress magnitudes are close. This is because the weather conditions were close during these days, which resulted in close vertical and lateral temperature gradients. The recorded maximum vertical temperature gradient and lateral temperature gradient in the experimental box-girder in 10-July-2013 were 17.66°C and 8.06°C, while they were 19.71°C and 8.39°C in 14-July-2014.

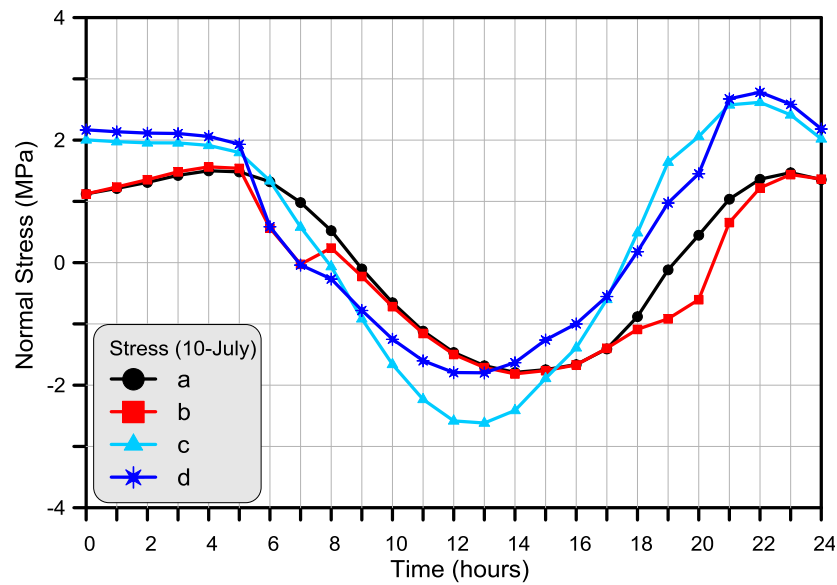


Figure 10.6 Normal stress variation in 10-July at points a, b, c, and d

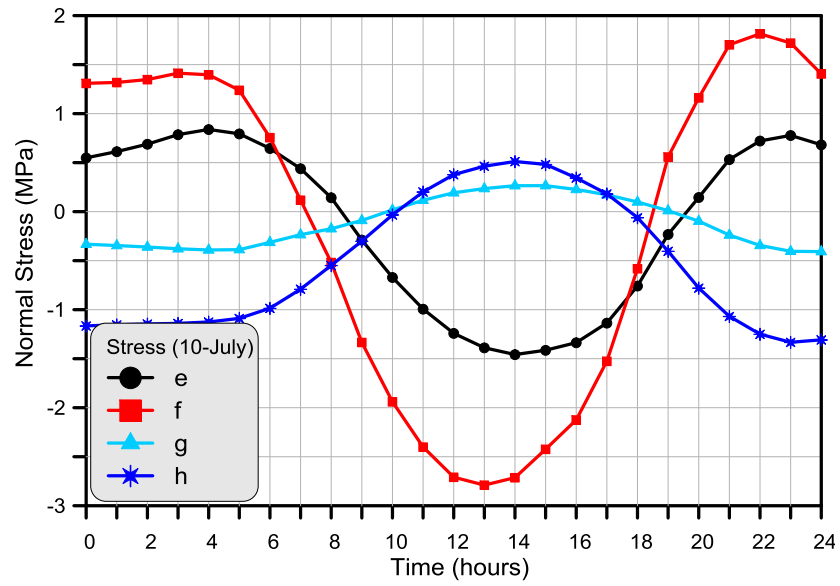


Figure 10.7 Normal stress variations in 10-July at points e, f, g, and h

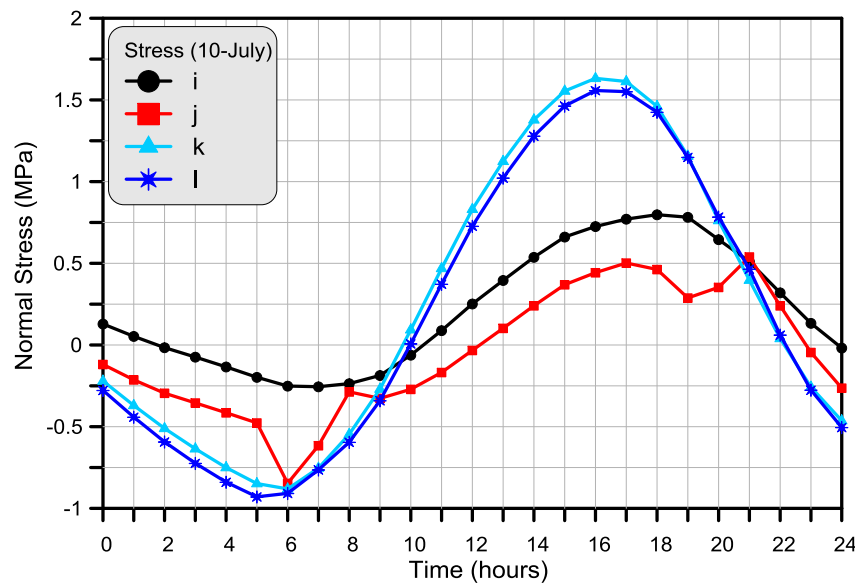


Figure 10.8 Normal stress variations in 10-July at points i, j, k, and l

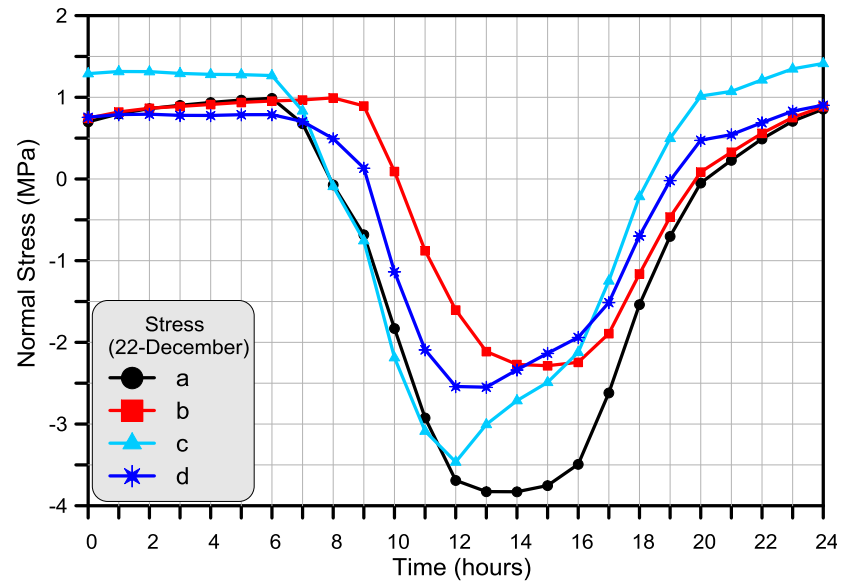


Figure 10.9 Normal stress variations in 22-December at points a, b, c, and d

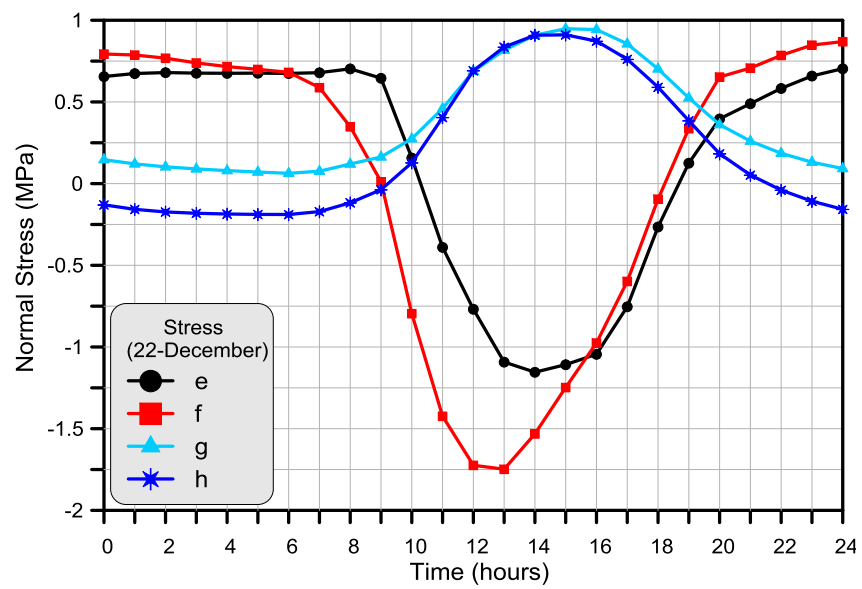


Figure 10.10 Normal stress variations in 22-December at points e, f, g, and h

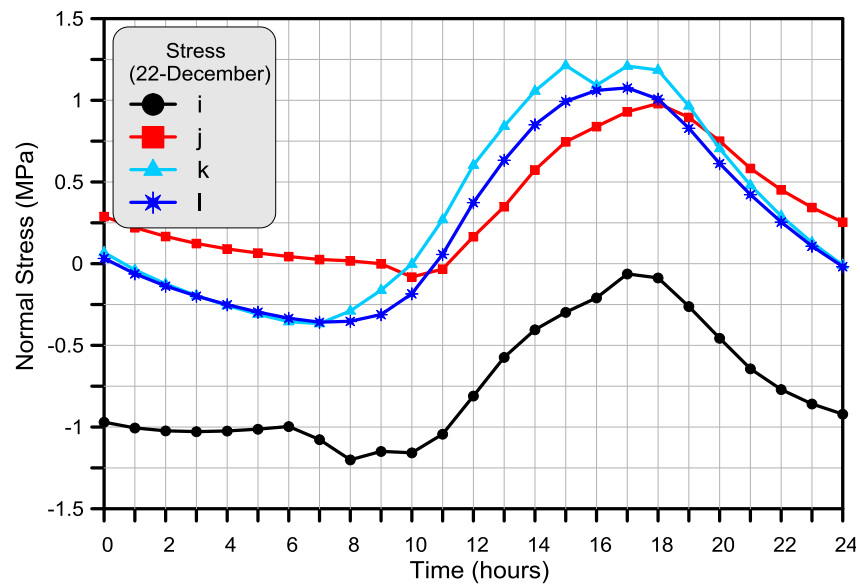


Figure 10.11 Normal stress variations in 22-December at points i, j, k, and l

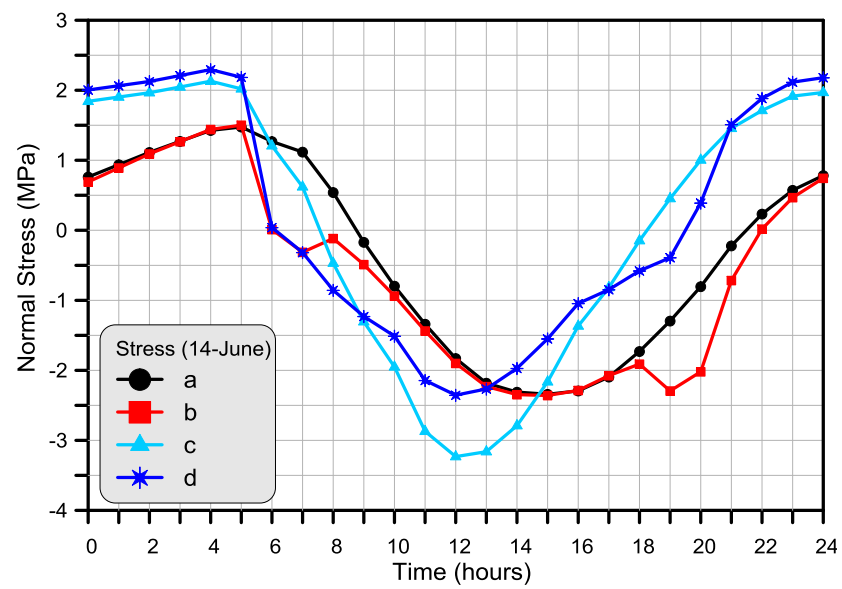


Figure 10.12 Normal stress variations in 14-June at points a, b, c, and d

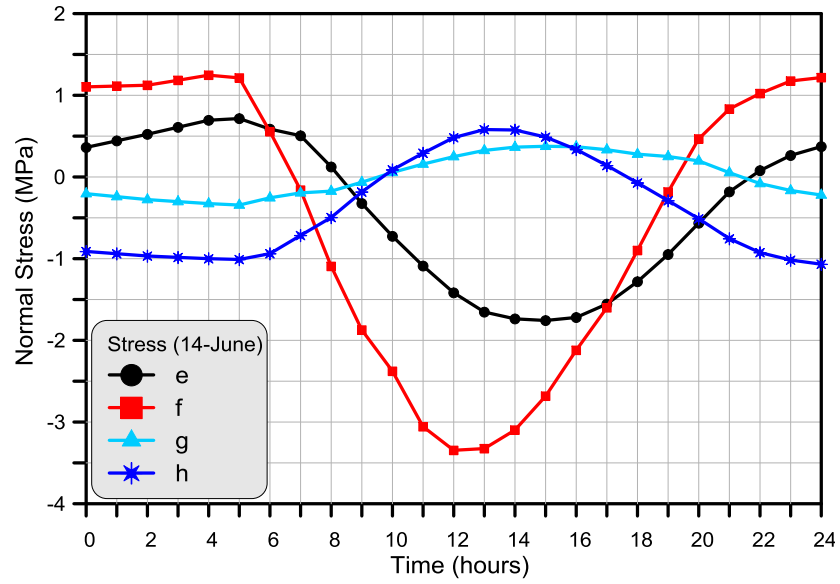


Figure 10.13 Normal stress variations in 14-June at points e, f, g, and h

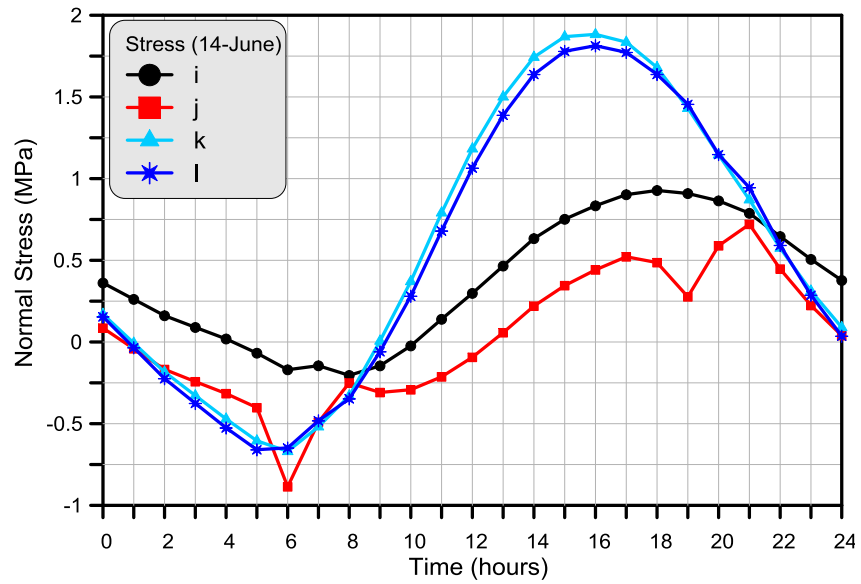


Figure 10.14 Normal stress variations in 14-June at points i, j, k, and l

10.4.1.2 Thermal Stress Variation at the centroidal Points during the 24 Hours

Figures 10.15 through 10.18 show the normal stress variation along the 24 hours at the centroidal points that are shown in Figure 10.4 during the three presented days (10-July, 22-December, and 14-June).

Figures 10.15 and 10.16 show that the behavior of the stresses at the centers of the top slab and bottom slab are almost the same, while the magnitudes of stresses are higher in the top slab. The stress behavior of the centroidal points, in general, is the inverse to that of the surface points that was discussed in the previous section. Tensile stresses increase during the day hours because the temperatures of these points become much lower than of the surface points.

As shown in Figures 10.15 and 10.16, tensile stresses occur at these points during December, while in summer (June and July), the stresses are compressive. In 10-July, the stresses in C_{TS} and C_{BS} ranged between -0.83 to 0.08 *MPa* and -0.31 to 0.02 *MPa*, respectively. In 14-June, the stress of C_{TS} ranged from -0.7 to 0.07 *MPa*, while at C_{BS} , it ranged from -0.23 to 0.04 . In 22-December, the stresses in C_{TS} and C_{BS} ranged between -0.02 to 0.47 *MPa* and 0.19 to 0.58 *MPa*, respectively.

Figure 10.17 shows the stress distributions at the centroid of the south web. Because of the same reasons discussed in the previous section for Figure 10.11 for the interior points i, j, k, and l, it is clear that the stress is tensile in June and July, while it is compressive in December for the centroidal point C_{SW} . The stress at C_{SW} in 22-December ranged from -1.4 *MPa* to -0.99 *MPa*. For 10-July and 14-June on the other hand, it was in the ranges of 0.09 *MPa* to 1.31 *MPa* and 0.22 *MPa* to 1.57 *MPa*, respectively.

The stresses at the centroid of the north web shown in Figure 10.18 were in the ranges of -0.24 *MPa* to 0.96 *MPa* in 10-July, -0.29 *MPa* to 1.02 *MPa* in 14-June, and 0.06 *MPa* to 0.82 *MPa* in 22-December.

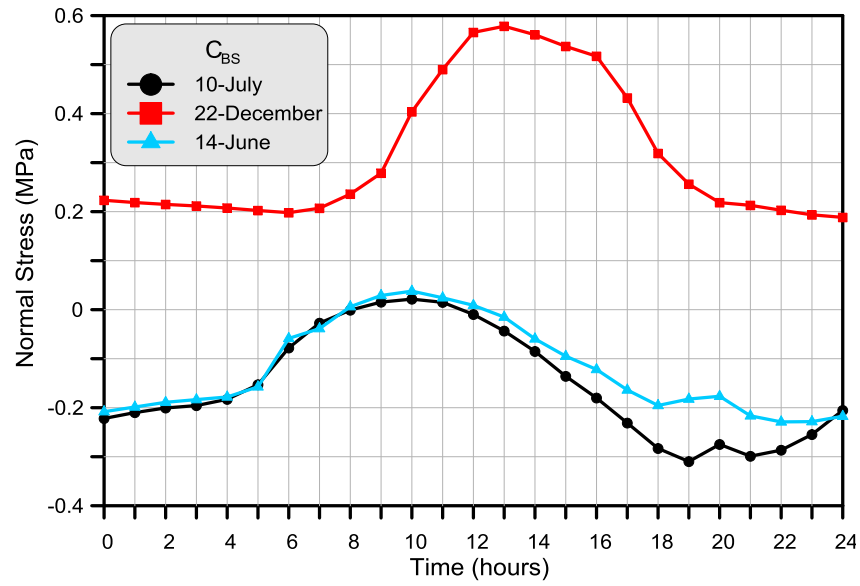


Figure 10.15 Normal stress variations at the central point C_{BS} along the three days

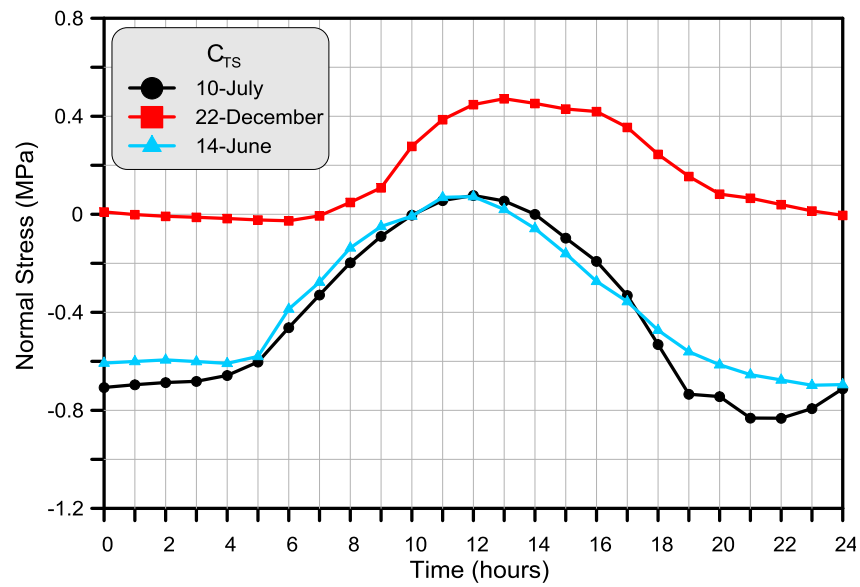


Figure 10.16 Normal stress variations at the central point C_{TS} along the three days

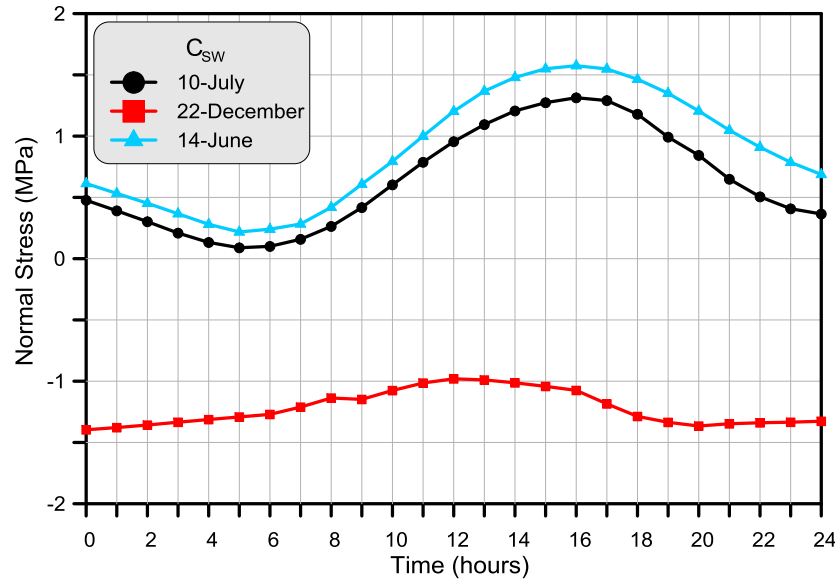


Figure 10.17 Normal stress variations at the central point C_{SW} along the three days

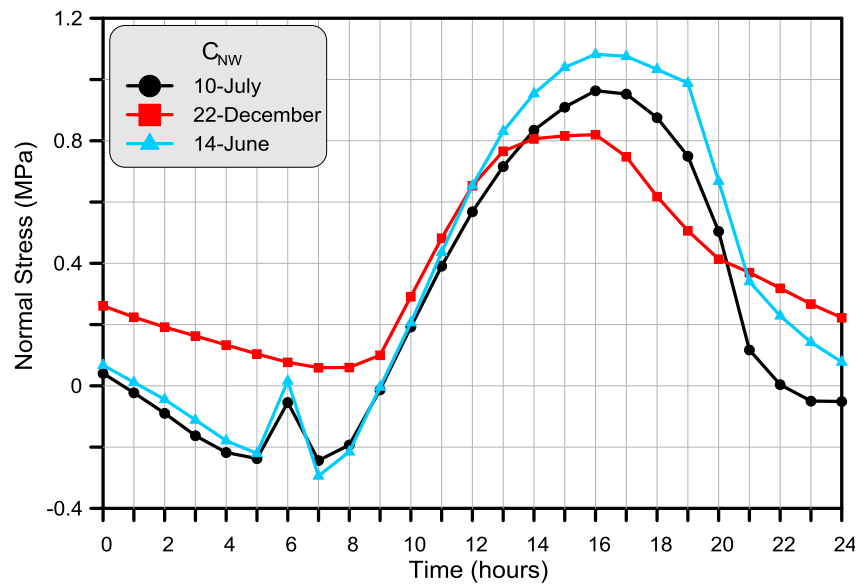


Figure 10.18 Normal stress variations at the central point C_{NW} along the three days

10.4.1.3 Vertical Thermal Stress Variations

In this section, the stress distributions are studied along the centerlines of the south and the north webs (sections A and B). The studied time steps are the times of the maximum tensile and compressive stresses at the top surfaces. The distributions across sections A and B are visualized for the three days of interest 10-July-2013, 22-December-2013, and 14-June 2014.

Figure 10.19 shows the vertical temperature distribution along section A. Comparing this figure with the temperature gradient distributions in the previous chapters, it is obvious that the shapes are similar but with reverse sign. During the hot hours of the day, the stress is compressive at the top and bottom fibers of the web (nearly the top 100 mm and the bottom 150 mm), while it is tensile along the rest interior height of the web as shown in the stress distribution at 1:00 PM in Figure 10.19. During the cold hours (late night and early morning hours), the top and bottom fibers become under tension followed by a stress reversing region as shown in Figure 10.19 at 10:00 PM, while the stress of the rest interior height of the webs is close to zero. Similar behavior is shown for the north web in Figure 10.20.

The maximum compressive stresses at the top surfaces of the south and north webs were recorded at 1:00 PM and were -2.56 MPa and -2.46 MPa , respectively. On the other hand, the maximum tensile stresses were recorded at 10:00 PM and were 1.82 MPa and 1.91 MPa , respectively.

At the bottom surface of the south web, the maximum compressive and maximum tensile stresses were -1.35 MPa at 3:00 PM and 0.94 at 4:00 AM. On the other hand, for the north web, the maximum compressive and tensile stresses at the bottom surface were -1.39 MPa at 2:00 PM and 0.92 MPa at 5:00 AM.

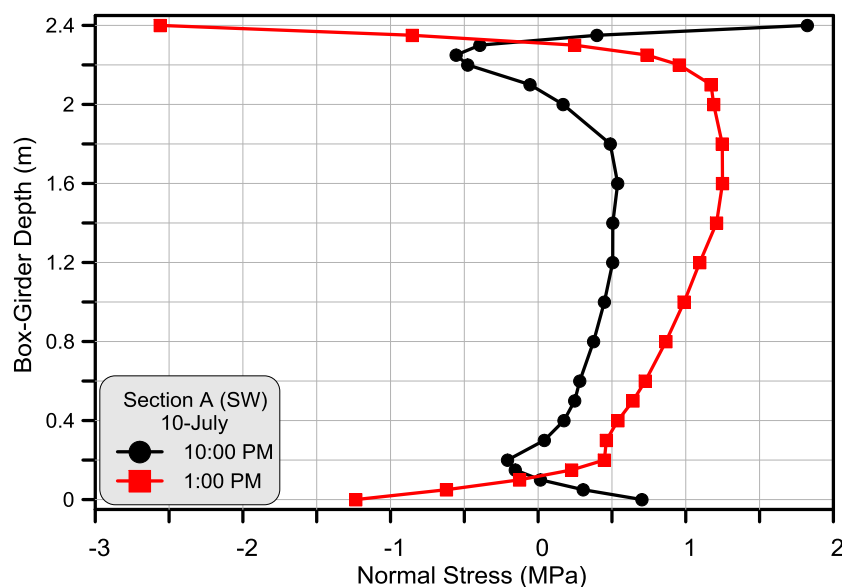


Figure 10.19 Normal stresses along the depth of the south web at different time steps in 10-July

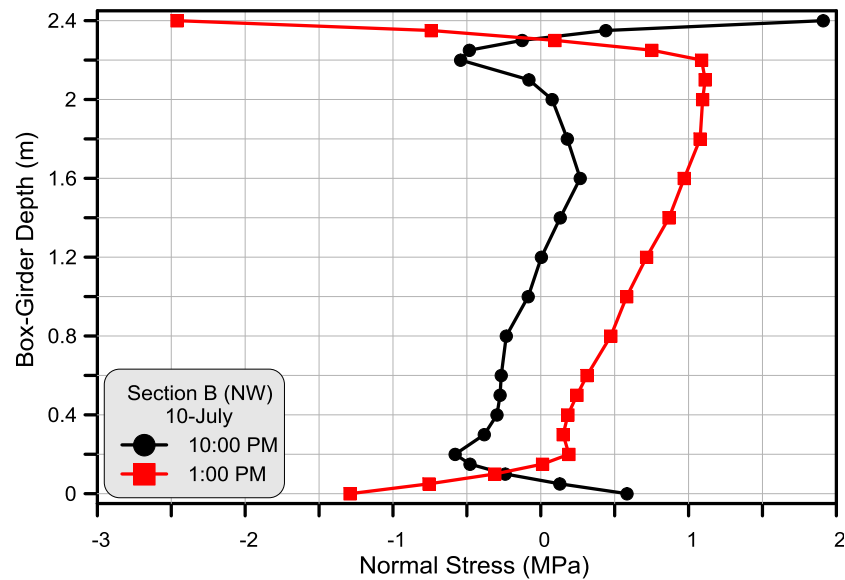


Figure 10.20 Normal stresses along the depth of the north web at different time steps in 10-July

Figure 10.22 shows that the stress distribution along the north web in 22-December is similar to that of 10-July, while the stress distribution along the south web shown in Figure 10.21 is different. The north web is shaded during the whole day in December and solar radiation received only from the top surface in addition to the reflected radiation on the bottom surface. On the other hand, the south web is directly subjected to concentrated solar radiations at low angles during the day, which results in much more heating on this surface compared to the exterior surface of the north web. As a result, the stress becomes compressive at the region of the south web that is heated by solar radiation as shown in Figure 10.21.

The maximum compressive stress at the top surface was -1.42 MPa , which occurred at 12:00 PM as shown in Figure 10.21, while the absolute maximum compressive stress in 22-December occurred at the bottom surface at 3:00 PM and was -1.85 MPa . On the other hand, the maximum tensile stress at the top surface occurred at midnight and was 0.92 MPa as shown in Figure 10.21, while the absolute maximum tensile stress was 1.12 MPa , which occurred 0.4 m below the top surface at 4:00 PM.

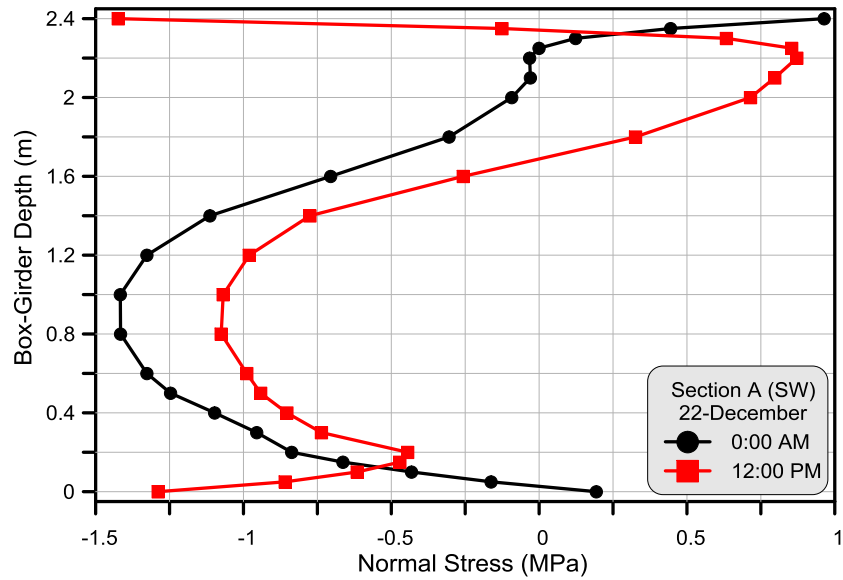


Figure 10.21 Normal stresses along the depth of the south web at different time steps in 22-December

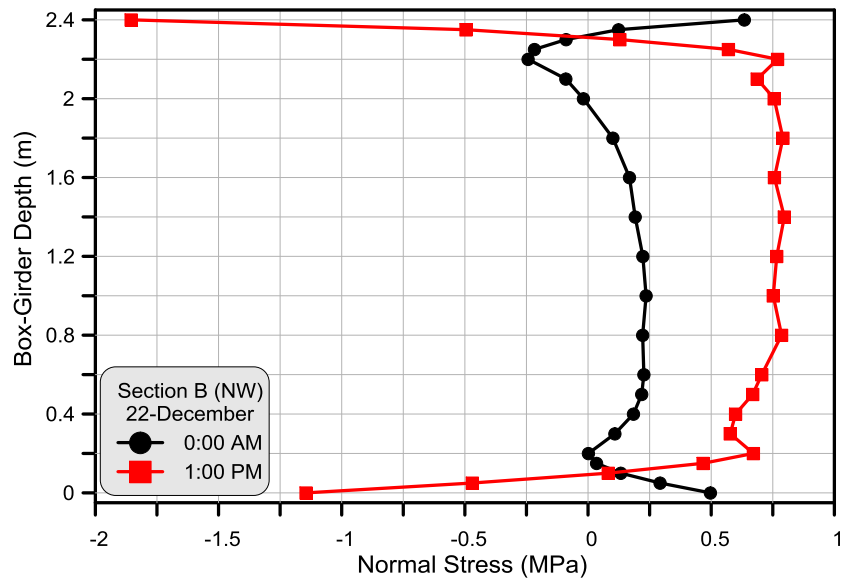


Figure 10.22 Normal stresses along the depth of the north web at different time steps in 22-December

Figures 10.23 and 10.24 show the distributions along the depth of the south and north webs in 14-June are quite similar to those discussed for 10-July in Figures 10.19 and 10.20. However, the stress values are different due to the different thermal load values. Figure 10.23 shows that the maximum compressive stress occurred at

the top surface of the south web at 12:00 PM and was -3.09 MPa . On the other hand, the maximum compressive stress at the top surface of the north web was -2.93 MPa , which also occurred at 12:00 PM as shown in Figure 10.24.

As shown in Figures 10.23 and 10.24, the maximum tensile stresses at the top surface along the south and the north webs were occurred at 4:00 AM, and were equal to 1.29 MPa and 1.39 MPa . Besides, the absolute maximum tensile stresses occurred along the south and the north webs were 1.91 MPa and 1.69 MPa , which were occurred 0.4 to 0.6 m below the top surface at 4:00 PM.

At the bottom surface of the south web, the maximum compressive and tensile stresses were -1.71 MPa and 0.88 MPa , which occurred at 3:00 PM and 5:00 AM, respectively. Their corresponding stresses at the bottom surface of the north web were -1.76 MPa and 0.8 MPa and occurred at 4:00 PM and 5:00 AM.

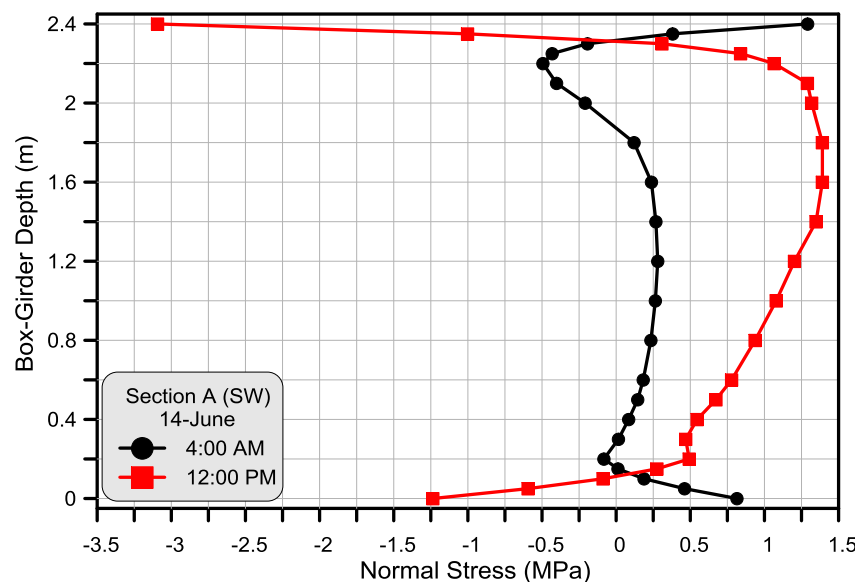


Figure 10.23 Normal stresses along the depth of the south web at different time steps in 14-June

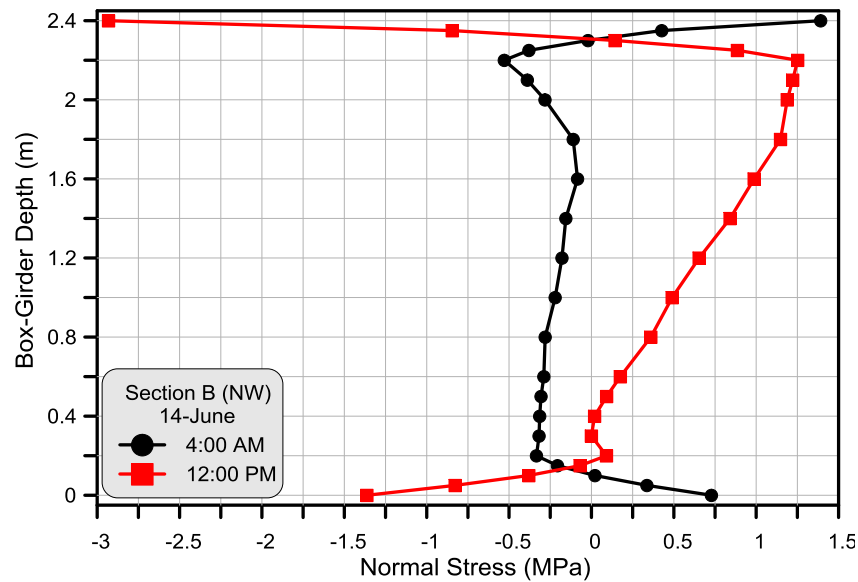


Figure 10.24 Normal stresses along the depth of the north web at different time steps in 14-June

10.4.1.4 Lateral Thermal Stress Variations

In this section, the stress distributions are studied for the three days along the centerlines of the top slab (section C) and the bottom slab (section D). As for the vertical stress distributions, the lateral stress distributions along the top slab in 10-July shown in Figure 10.25 have similar shape to the corresponding lateral temperature gradients but with reversed signs. Because the temperature is almost constant along the top slab during the noon hours, the stress is almost zero at this region. On the other hand, the southern end is being heated by the solar radiation, which results in a compressive stress, while the stress in the northern shaded end is tensile as shown in Figure 10.25 for the stress distribution at 2:00 PM. During the cooling hours, the ends are subjected to faster cooling due to the greater surface area, while the interior points still warm because of the large amount of heat conducted from the top surface during the day, which resulted in the stress distribution shown in Figure 10.25 (at 4:00 AM).

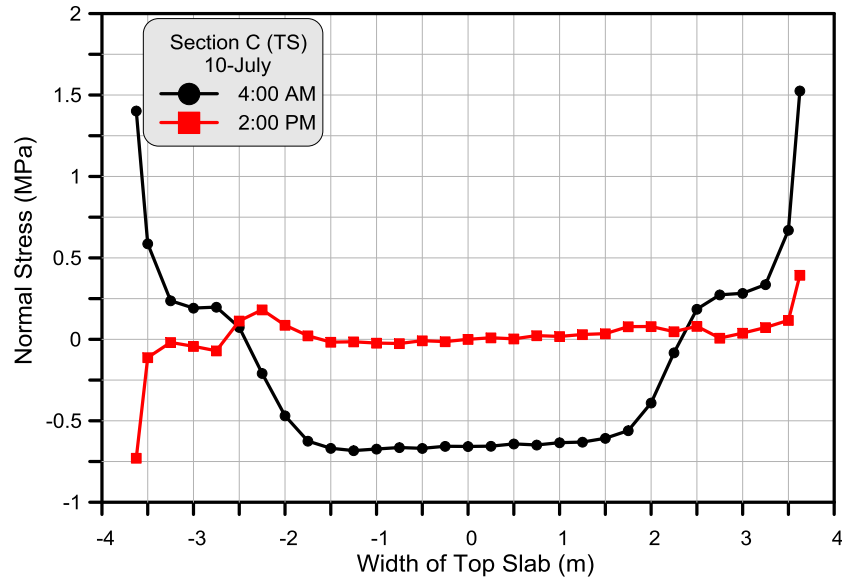


Figure 10.25 Normal stresses along the width of the top slab at different time steps in 10-July

The maximum compressive stress along section C in 10-July was recorded at 7:00 PM and was -1.0 MPa , while the maximum end compressive stress was recorded at the southern end at 2:00 PM, which was -0.72 MPa as shown in Figure 10.25. On the other hand, the maximum tensile stress was 1.59 MPa , which was recorded at the northern end at 4:00 AM as shown in Figure 10.25.

Figure 10.26 shows that the stress is almost zero along the interior width of the bottom slab in 10-July, both at 4:00 AM and 7:00 PM, while it is tensile at the ends at 4:00 AM with a maximum of 1.08 MPa . Moreover, the maximum compressive stress was recorded at the northern end at 7:00 PM and was -1.12 MPa because of the concentrated solar radiation on the vertical northern surfaces before the sunset.

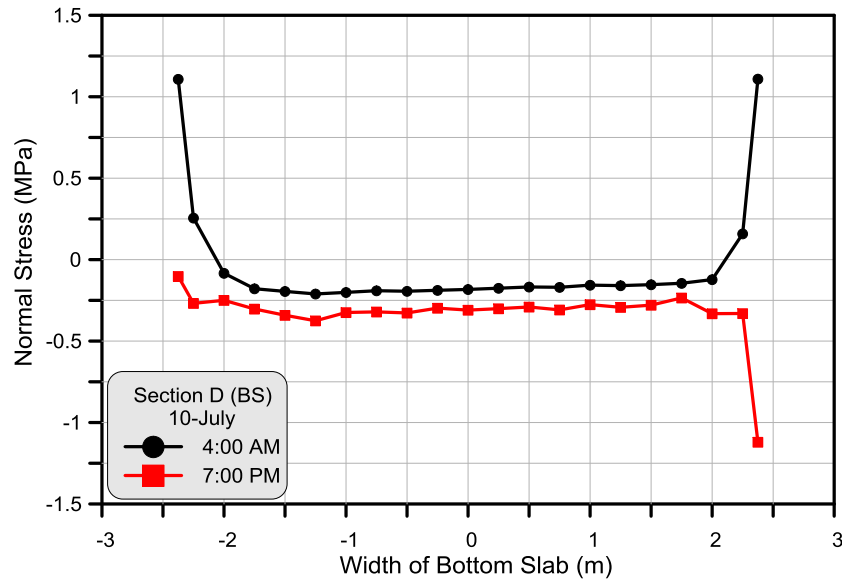


Figure 10.26 Normal stresses along the width of the bottom slab at different time steps in 10-July

Figures 10.27 and 10.28 illustrate the effect of the high solar radiation on vertical surfaces in winter where the compressive stresses are high at the southern edge of the top and bottom slab, which are fully exposed to solar radiations during the whole day hours. The maximum compressive stresses at the southern edge of the top slab in 22-December was -2.65 MPa , which occurred at 12:00 PM as shown in Figure 10.27, while the maximum compressive stress at the southern edge of the bottom slab, which is shown in Figure 10.28, was -3.53 MPa and occurred at 1:00 PM. The stress along the interior length of the bottom slab was tensile along the full day and was less than 0.73 MPa as shown in Figure 10.28, while the stress along the interior six meters of the top slab was between about -0.4 MPa and 0.8 MPa , as shown in Figure 10.27.

In 14-June, the maximum compressive stress along the top slab occurred at the northern edge at 7:00 PM and was -1.1 MPa , while the maximum tensile stress was 1.52 MPa , which occurred at 5:00 AM at the northern edge as shown in Figure 10.29.

Along the bottom slab in 14-June shown in Figure 10.30, the maximum compressive stress was -2.1 MPa and was recorded at the northern edge at 7:00 PM, while the

maximum tensile stresses at the southern and northern edges at 5:00 AM were 1.05 MPa and 1.0 MPa.

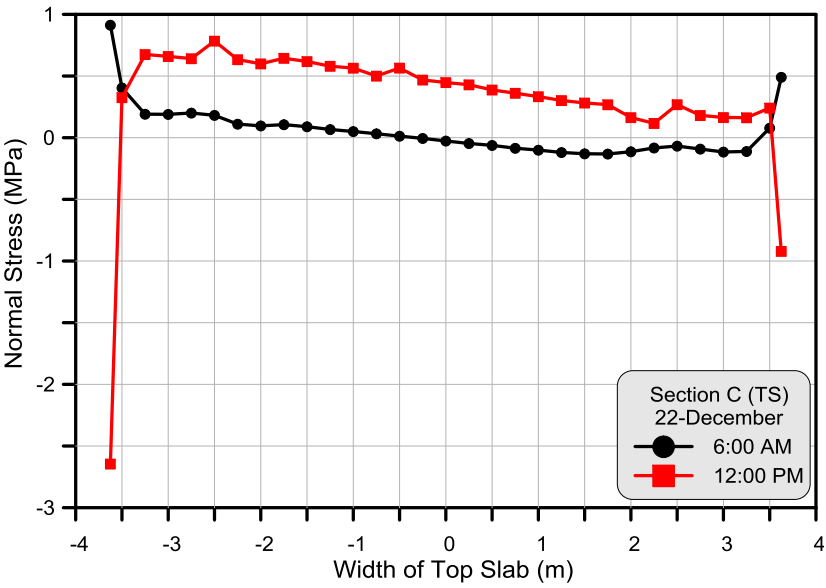


Figure 10.27 Normal stresses along the width of the top slab at different time steps in 22-December

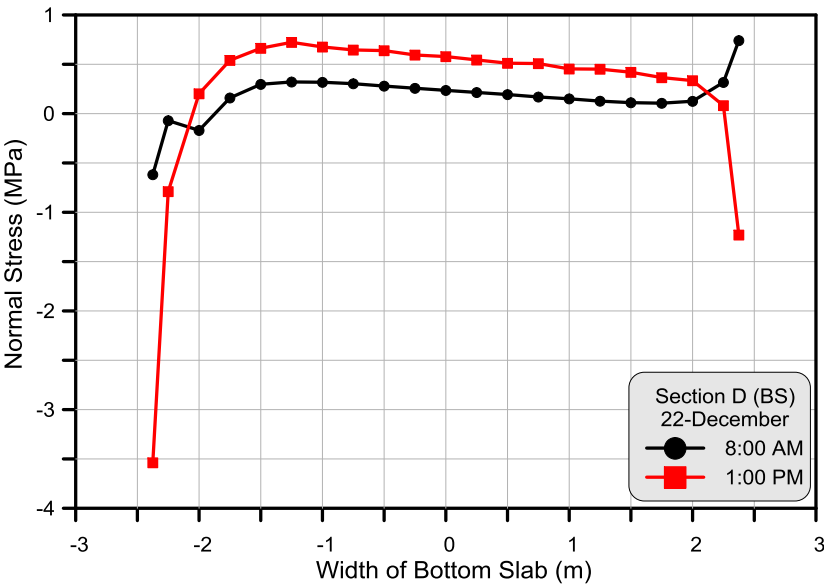


Figure 10.28 Normal stresses along the width of the bottom slab at different time steps in 22-December

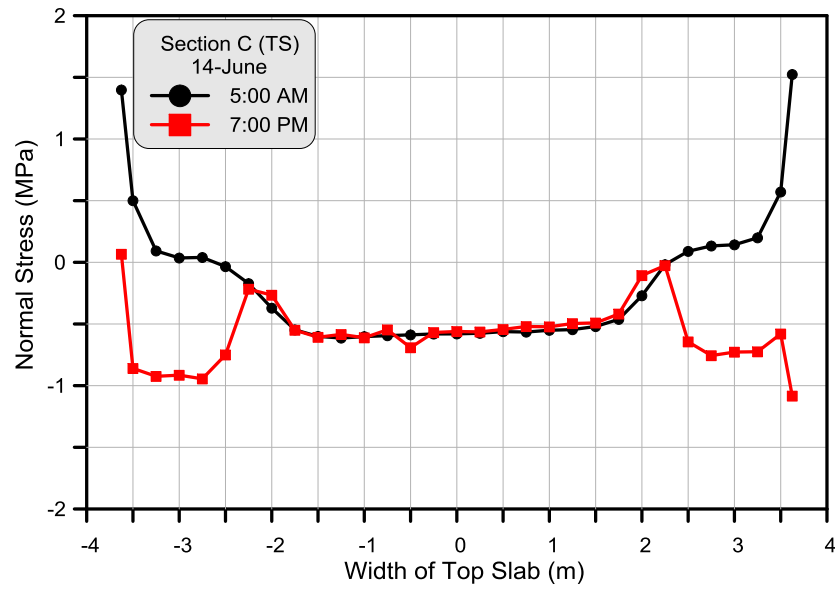


Figure 10.29 Normal stresses along the width of the top slab at different time steps in 14-June

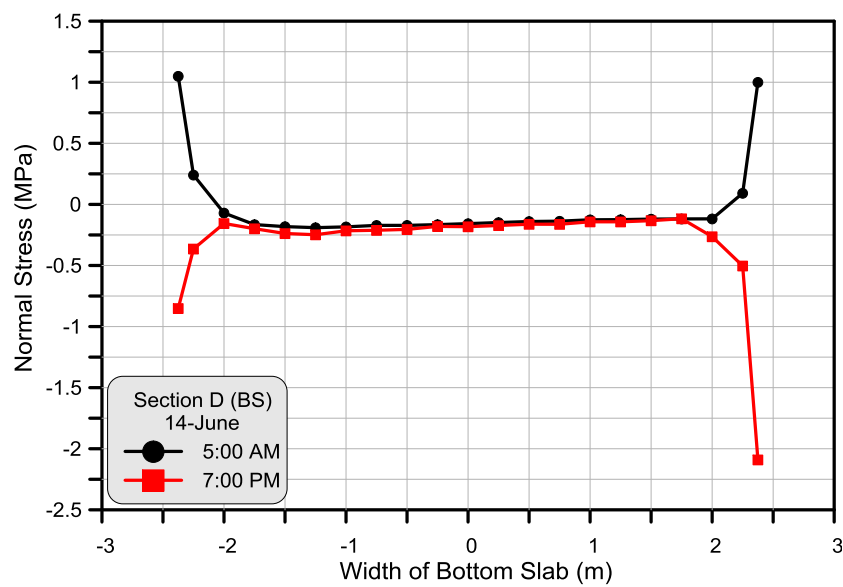


Figure 10.30 Normal stresses along the width of the bottom slab at different time steps in 14-June

10.4.2 Thermal Displacements

The vertical and lateral displacements due to the thermal loads of the three selected days 10-July-2013, 22-December-2013, and 14-June-2014 are visualized and discussed in this section. The vertical displacements are drawn at the mid span at points e and f shown in Figure 10.4. Point e is located at the mid-width of the bottom surface of the bottom slab, while point f is located at the mid-width of the top surface of the top slab. On the other hand, lateral displacements are drawn at the corner points of the bottom surface of the bottom slab (a and b) and at the corner points of the top surface of the top slab (c and d), which are shown in Figure 10.4. In addition, the 3D view of the deformed box-girder is shown for the maximum vertical and lateral displacements in the investigated days.

Figure 10.31 shows that the vertical deflections of points e and f are almost identical along the 24 hours of 10-July. The deflection (vertical displacement) is small during the night hours and approaches to zero during the early morning hours (before the sunrise) because the vertical temperature gradient is minimal during this time. Oppositely, the deflection increases during the hot sunny hours reaching its peak at 4:00 PM and 5:00 PM due to the high vertical temperature gradients. The vertical displacement between 1:00 PM and 7:00 PM ranged from about 8 *mm* to more than 10 *mm*, with a maximum vertical displacement of 10.51 *mm* at 5:00 PM as shown in Figure 10.31. Figure 10.33 shows that at each section, all the points have almost the same vertical displacement.

The lateral displacement variations along the 24 hours of 10-July at points a, b, c, and d show different behaviors as shown in Figure 10.32. Point c and d at the southern and northern edges of the top slab show opposite sign of concaving. This is because as discussed in the previous chapters, in summer, the north edge is subjected to sunrays during the early hours after sunrise and during the latest hours before the sunset, while at this time, the southern edge is fully shaded. The opposite stands during the mid day hours, the northern edge becomes shaded, while the southern is directly subjected to solar radiation.

In general, the lateral displacement in summer is much lower than the vertical displacement. Among the four points, the maximum displacement was at point d at 4:00 PM, which was 0.9 *mm*, while the overall maximum lateral displacement in

10-July was 0.92 mm and was recorded at the northern edge at 8:00 PM as shown in Figure 10.34.

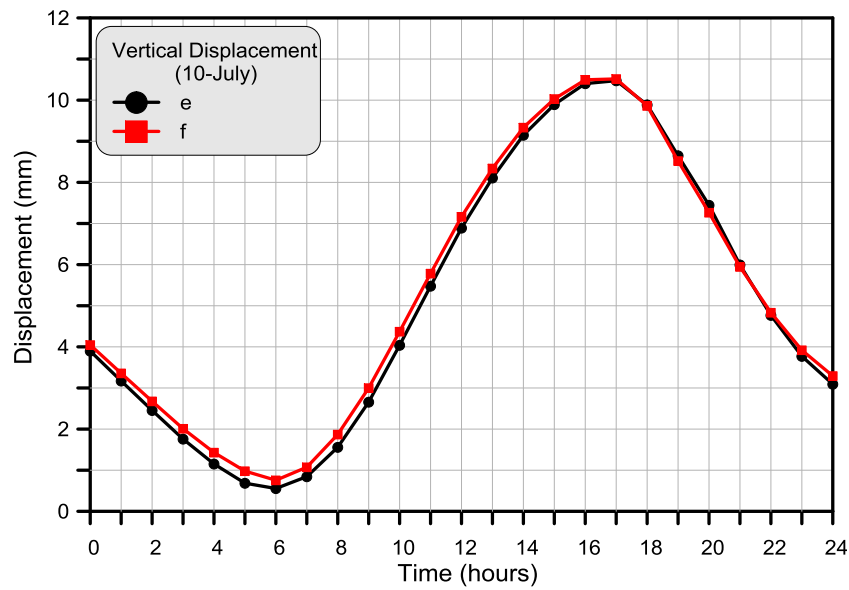


Figure 10.31 Vertical displacement variations in 10-July at points e and f

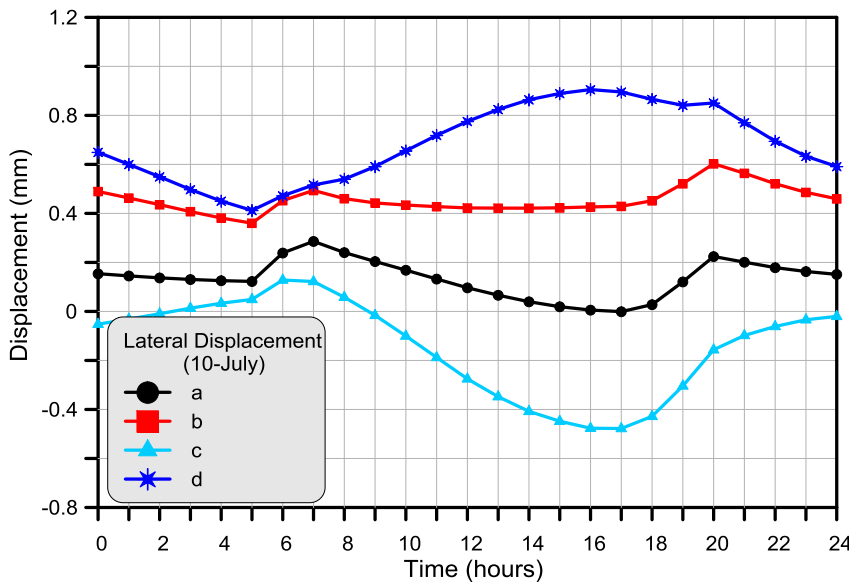


Figure 10.32 Lateral displacement variations in 10-July at points a, b, c, and d

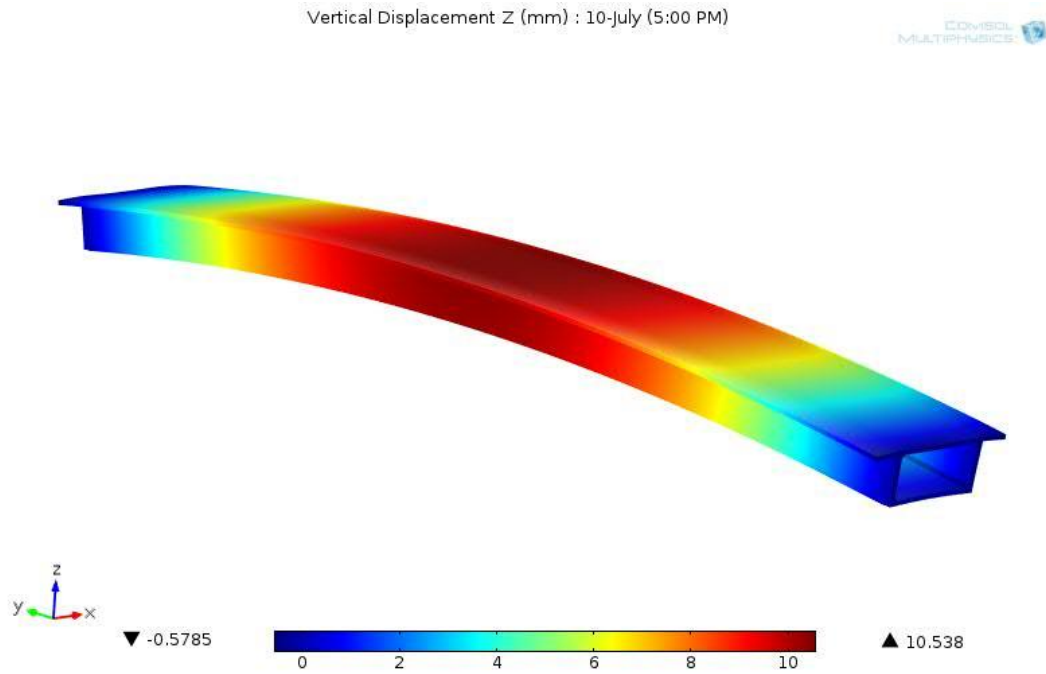


Figure 10.33 3D view of vertical displacement in 10-July at 5:00 PM

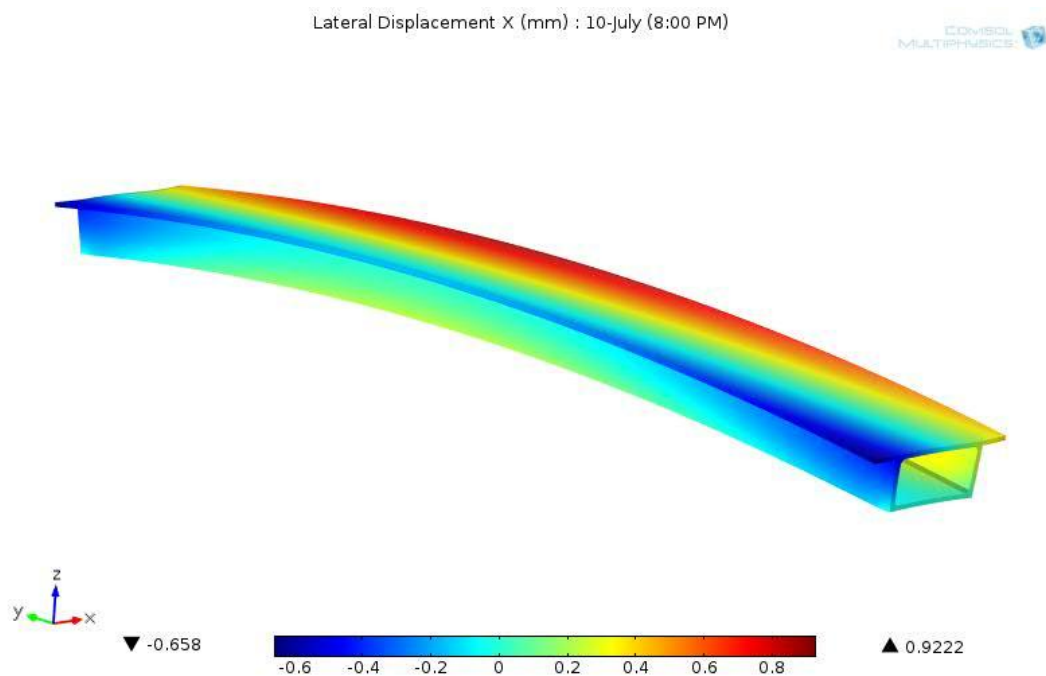


Figure 10.34 3D view of lateral displacement in 10-July at 8:00 PM

Figure 10.35 shows the vertical displacements at points e and f in 22-December. As shown, the vertical displacement is small and ranges from negative due to the cooling effect of the winter nights to positive due to the heating of the sunny hours.

The vertical displacement at point e in 22-December ranged from -1.54 mm at 7:00 AM to 2.54 mm at 3:00 PM, while the overall maximum vertical displacement was recorded at 4:00 PM and was 2.73 mm as shown in Figure 10.37.

The lateral displacement variations in 22-December shown in Figure 10.36, show that the southern edge points a and c exhibited larger lateral displacements than the northern edge points b and d. This is because in winter, the sun strikes the southern vertical surfaces during the full day hours, while the northern edges are fully shaded.

The maximum lateral displacements at points a and c were recorded at 4:00 PM, which were -1.68 mm and -1.79 mm , while the maximum lateral displacement recorded for the box-girder was -1.86 mm , which was also recorded at 4:00 PM as shown in Figure 10.38.

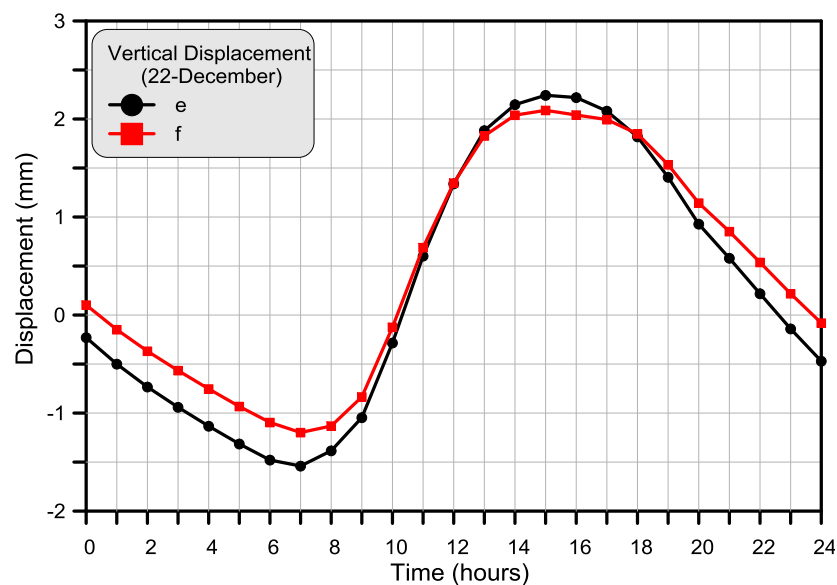


Figure 10.35 Vertical displacement variations in 22-December at points e and f

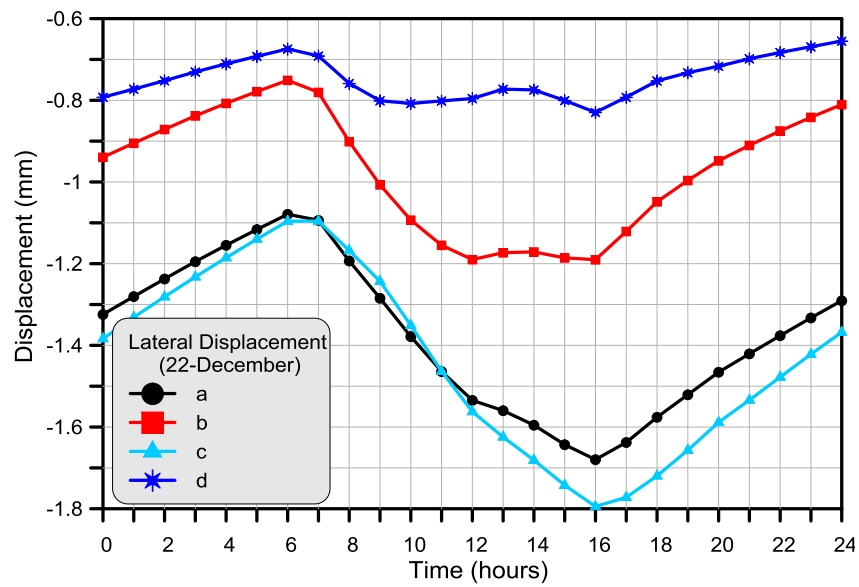


Figure 10.36 Lateral displacement variations in 22-December at points a, b, c, and d

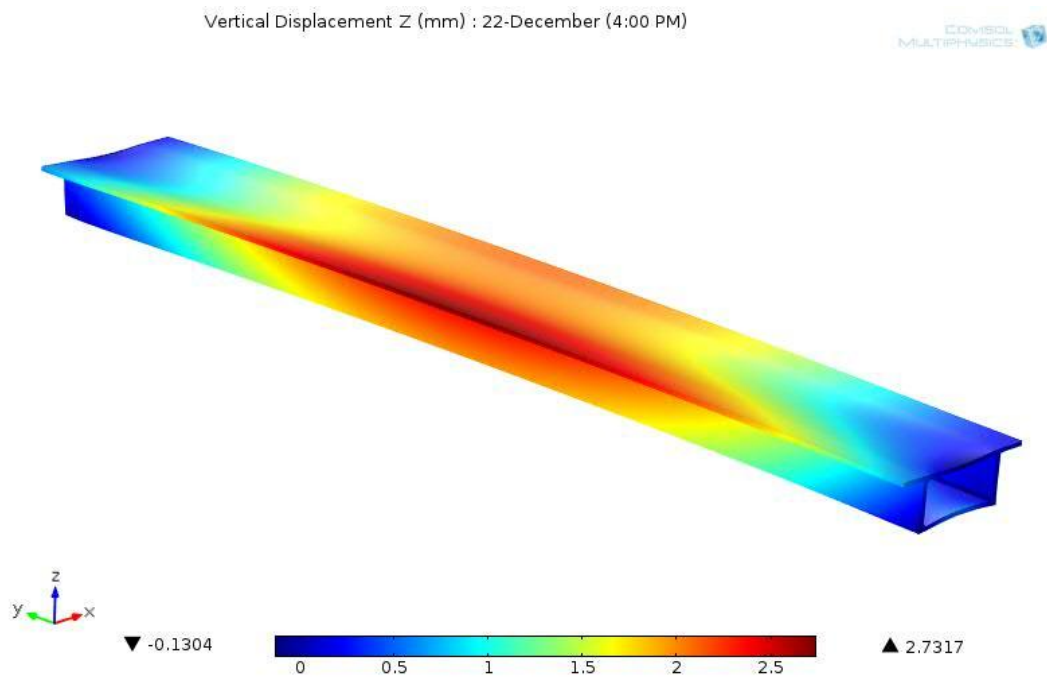


Figure 10.37 3D view of vertical displacement in 22-December at 4:00 PM

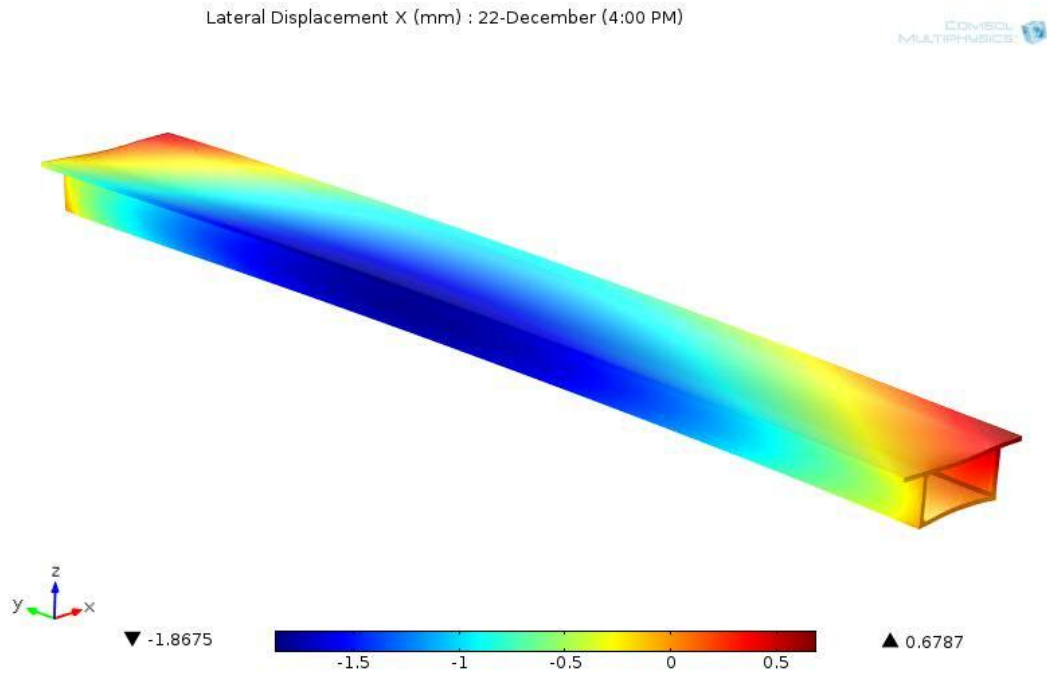


Figure 10.38 3D view of lateral displacement in 22-December at 4:00 PM

Figures 10.39 and 10.40 show the vertical and lateral displacement variations in 14-June at the six points. It is shown in Figure 10.39 that the vertical displacement at e and f are almost identical as discussed for Figure 10.31. The vertical displacement at the points e and f in 14-June ranged between 1.73 mm and 12.47 mm . Figure 10.41 shows that a maximum vertical displacement of 12.48 mm was recorded at 3:00 PM in 14-June.

Figure 10.40 shows the lateral displacement variations of the points a, b, c, and d in 14-June. It is obvious that the behaviors are similar to those of 10-July. The lateral displacements of the four points ranged from -0.48 mm at point c to 1.17 mm at point d, while Figure 10.42 shows that the maximum lateral displacement was recorded at 8:00 PM and was 1.25 mm .

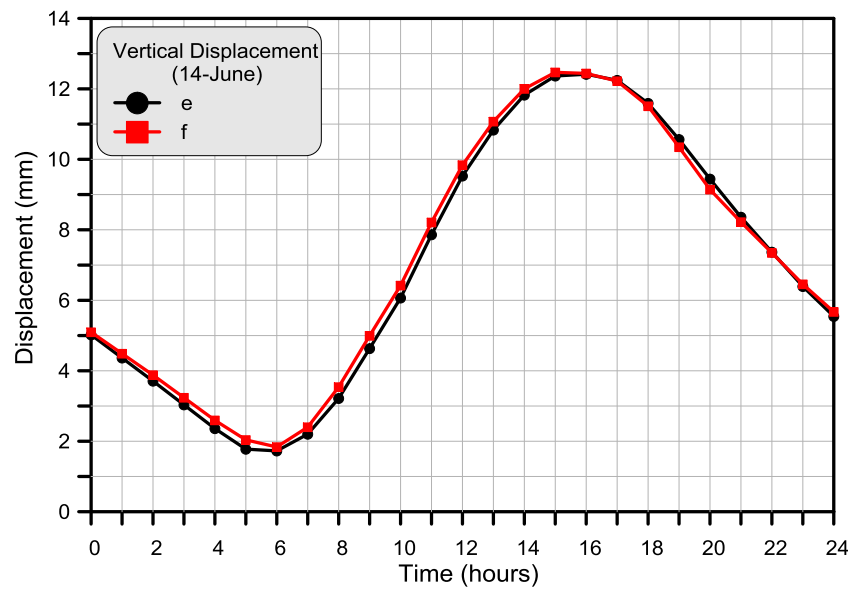


Figure 10.39 Vertical displacement variations in 14-June at points e and f

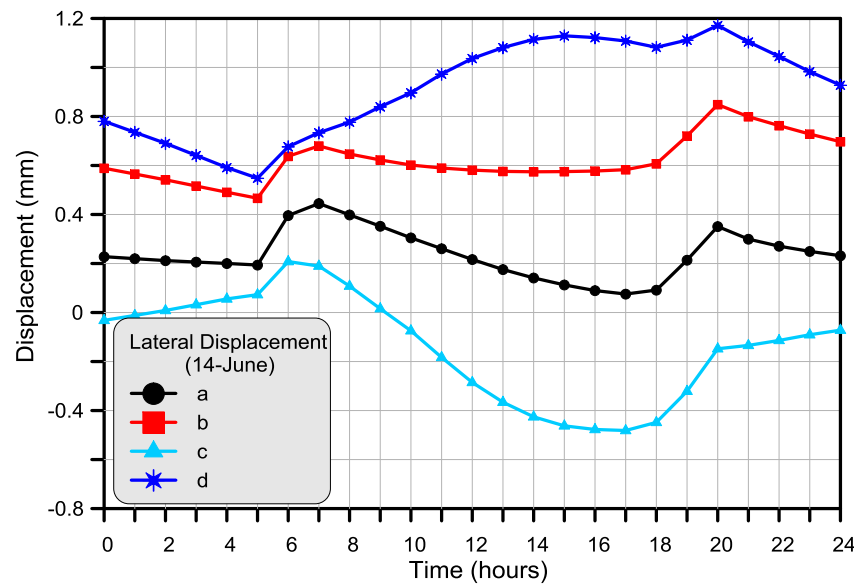


Figure 10.40 Lateral displacement variations in 14-June at points a, b, c, and d

Vertical Displacement Z (mm) : 14-June (3:00 PM)

COMSOL
MULTIPHYSICS

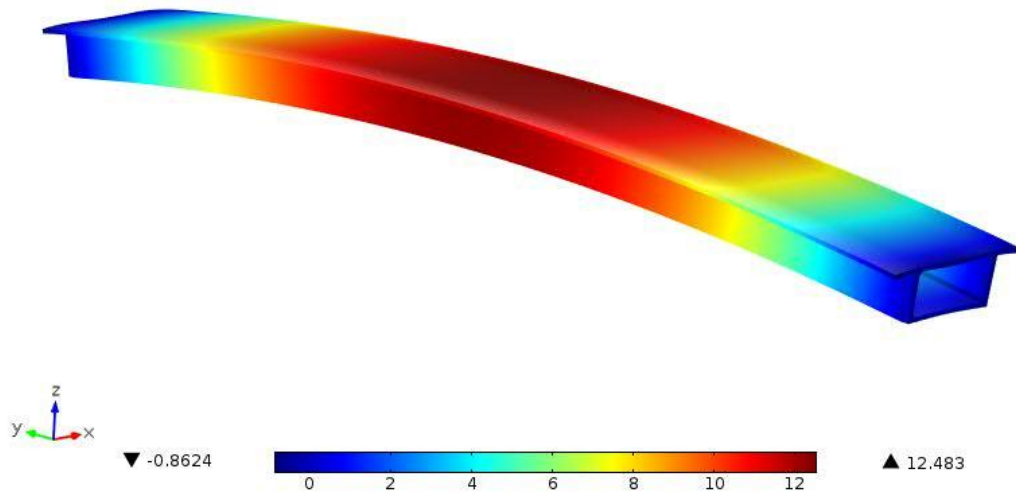


Figure 10.41 3D view of vertical displacement in 14-June at 3:00 PM

Lateral Displacement X (mm) : 14-June (8:00 PM)

COMSOL
MULTIPHYSICS

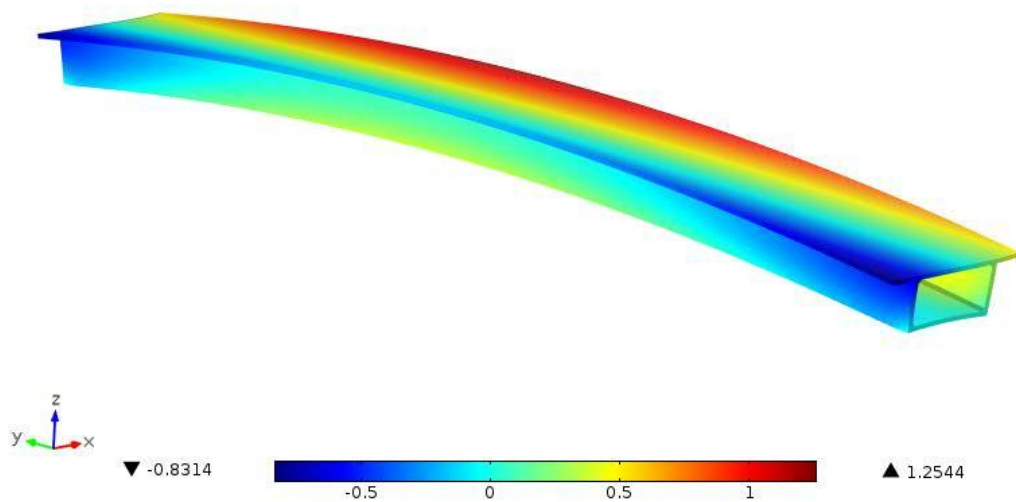


Figure 10.42 3D view of lateral displacement in 14-June at 8:00 PM

CHAPTER ELEVEN

CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

The work of the current research composed mainly of four parts. The first part is the experimental work, in which a full-scale reinforced concrete box-girder bridge segment was constructed on a reinforced concrete supporting frame. The bridge segment was instrumented with many thermocouples in addition to a weather station, which includes air temperature, solar radiation and wind speed sensors. The second part is a three-dimensional finite element analysis of the heat transfer and temperature distributions in the experimental box-girders. The heat transfer finite element model was then used to conduct several studies including geometrical and material parametric studies. The third part attempted to use the heat transfer finite element model, the results of the parametric studies, and long-term (30 to 50 years) records of air temperature and solar radiation for the different regions of Turkey to propose thermal actions provisions for concrete bridges in Turkey. In the fourth part, a thermo-mechanical finite element analysis was conducted to investigate the effect of the environmental thermal loads on the structural behavior of the full-length span of the experimental box-girder considering the thermal loads measurements from the current experimental work in Gaziantep. The main conclusions from the four aforementioned parts of the work are as follows:

11.1.1 The Experimental Work

Based on the experimental measurements from the thermocouples and the weather station, the followings are concluded:

- 1- Within few hours from concrete casting, the hydration heat's influence on the temperature distributions in the experimental box-girder segment was significant.

The effect of hydration heat reached its peak value after approximately 12 hours from concrete casting. Beyond peak, this effect started to decrease gradually. After approximately 2 days, the effect of hydration heat significantly decreased until it almost diminished after approximately 4 days.

2- Two factors were found to be effective on temperature distributions during the early age of concrete. The first is the location of the thermocouple in the box-girder with respect to the exposed surfaces, while the second is the sealant degree from the formwork of the adjacent exterior surfaces. Thermocouples that were installed deep in the concrete mass, such as SW7 and NW7, and those that were surrounded by sealed surfaces, showed higher degree of influence of the hydration heat. These thermocouples exhibited higher temperatures and were more influenced by the hydration heat-time behavior compared to other thermocouples. On the other hand, surface thermocouples such as SW1 and NW1 followed the air temperature-time variation and showed less dependency on hydration heat.

3- Due to the effect of hydration heat during the first day, inverse (negative) temperature gradients took place along the vertical webs, where the top surface was colder than the interiors. These inverse temperature gradients occurred due to the concentration of hydration heat in the concrete cores, where heat production rate there was higher than heat dissipation at the exterior surfaces. This behavior decreased gradually during the following two days showing similar behavior to that of aged concrete. A maximum negative gradient of approximately 25 °C was recorded 12 hours after concrete casing.

4- The temperature measurements of 62 thermocouples along a one-year period showed that the differences between the recorded daily maximum and minimum temperatures were more significant for surface thermocouples than for interior thermocouples. For the thermocouples SW1 (top surface) and SW6 (0.2 m in the concrete), the recorded maximum daily temperature differences were 26.7 and 18°C, while they were 20.5 and 10.4°C for SW9 (exterior surface of the web) and SW11 (interior surface of the web). Similarly, the maximum daily temperature differences for thermocouples TS1 (edge of the top slab) and TS9 (center of the top slab) were 28.9 and 15.9°C, while for thermocouples BS1 (edge of the bottom slab) and BS5 (center of the bottom slab) were 19.4 and 9.2°C.

5- During the mid-day hours of the summer's hot days, sunrays strike at high altitude angles, which leads to the concentration of solar radiation on the top surface of the box-girder. This leads to a jump in the temperature of the top fibers of the top slab compared to the subsequent fibers along the height of the girder. As a result, high vertical temperature gradients occurred in summer compared to in the other seasons. For the whole test period, the maximum vertical temperature gradient was recorded in 14-June, which was approximately 20°C. On the other hand, the maximum vertical temperature gradients in the other seasons were recorded in 22-March, 11-October, and 22-December, which were 16.6, 14.2, and 11.1°C, respectively.

6- In contrary to summer and due to the low altitude angles of sunrays in winter and autumn, the intensity of solar radiation on vertical surfaces (webs and edges of slabs) is higher than on the top slab. Consequently, the recorded lateral temperature gradients along the slabs were higher than the vertical temperature gradients along the webs in winter and autumn. In 22-March, 14-June, 11-October, and 22-December, the recorded maximum lateral temperature gradients were 15.2, 8.4, 18.4, and 19°C, respectively along the top slab, while they were 11.5, 5.4, 13.8, and 15.1°C, respectively along the bottom slab.

7- The maximum vertical temperature gradient on the top surface was found to be better correlated to the daily total solar radiation than to the daily air temperature difference. The coefficient of determination R^2 of the quadratic relation of the daily maximum vertical temperature gradient with the daily total solar radiation was 0.9, while it was only 0.42 with the daily air temperature difference.

8- The experimental records of concrete temperatures, air temperature, solar radiation, and wind speed from this study were utilized to introduce a simple formula that can predict the maximum vertical temperature gradient at the top surface of concrete bridge superstructures. The R^2 between the predicted vertical temperature gradients from the proposed formula and the experimental measurements was approximately 0.96. Similarly, two more formulas were introduced to estimate the maximum lateral temperature gradients along the top and bottom slabs of box-girders. The R^2 of the proposed formulas were approximately 0.92 and 0.94 for the top slab and the bottom slab, respectively.

9- The daily maximum and minimum mean temperatures of the experimental box-girder segment were found to be very well linearly correlated to the daily maximum and minimum air temperatures, respectively. The R^2 value of the proposed linear formula between the daily maximum bridge mean temperature and the daily maximum air temperature was approximately 0.97, while it was approximately 0.96 between the daily minimum bridge mean temperature and the daily minimum air temperature.

11.1.2 The Heat Transfer Finite Element Analysis and the Parametric Studies

The followings are the main conclusions drawn from the heat transfer finite element analysis and the parametric studies:

1- Good agreement was found between the recorded concrete temperatures from the experimental box-girder segment and the corresponding temperatures that were predicted by the heat transfer finite element analysis over the different parts of the box-girder. The mean absolute error between the recorded and the predicted concrete temperatures was in the range of 0.4 to 2.1 °C, while the maximum absolute error was in the range of 0.7 to 3.2 °C.

2- The effects of the thermal properties of concrete on the temperature distributions and variations in concrete box-girder bridges were investigated using individual and combined finite element parametric studies. Within the investigated ranges of material properties, one-way ANOVA showed that both concrete density and surface emissivity were of negligible effects. On the other hand, thermal conductivity, specific heat, and solar absorptivity showed different levels of effects on concrete temperature distributions.

3- The results of the individual parametric studies showed that solar absorptivity was more effective than thermal conductivity and specific heat. When solar absorptivity changed from 0.5 to 0.7, the maximum temperature difference increased by 15%. On the other hand, as thermal conductivity decreased from 2.5 to 1.3 W/mK , the maximum temperature difference increased by 7.8%, while as the specific heat decreased from 1200 to 800 J/kgK , the temperature difference increased by 9.2%. Moreover, the parametric studies showed that the combined effect of solar

absorptivity, thermal conductivity, and specific heat led to greater effects on the temperature distributions and variations than their individual effects. The hourly difference between the maximum and minimum bridge temperatures increased by approximately 70% by the changing of the three thermal properties from case 3 ($a = 0.5$, $C_p = 1200$, and $k = 2.5$) to case 1 ($a = 0.7$, $C_p = 800$, and $k = 1.3$).

4- The E-W orientation resulted in the highest summer positive vertical temperature gradient, while the orientations N-S and NE-SW in which one of the webs faces the sunrise and the other one faces the sunset resulted in the highest lateral temperature gradients both along the slabs and across the webs.

5- The box-girder depth has a small effect on the value of the maximum positive temperature gradient for depths shallower than 5m, while it becomes ineffective for deeper box-girders. The vertical temperature gradient increased by about 1.6°C for depths from 1.0 to 5.0 m, while it was almost constant from 5.0 to 12.5 m. Another important note is that the point of zero gradient from the top surface was 1.2 m for box-girder depths from 2 to 10 m, while it was 1.5 m for depth of 12.5 m. Moreover, the effect of the box-girder depth is clear on the lateral temperature gradients across the webs. The lateral gradient decreases with the decrease of the depth due to the effect of shadowing from the cantilever portions. However, this effect becomes negligible for deep sections (more than 7.5 m).

6- For the mid day hours, the cantilever width has a direct impact on the degree of shading of webs and thus on the lateral temperature gradient. On the other hand, before the sunset, sunrays have generally lower altitudes and hence there is no effect of shading, which minimizes the effect of the width of the cantilever portion.

7- The temperature along the centerline of the top slab becomes less affected by the top surface heating and hence becomes lower as the thickness of the top slab increase. On the other hand, the maximum positive lateral temperature gradient along the bottom slab increased by approximately 35% as the thickness of the bottom slab increased from 0.2 to 0.5 m. Moreover, the maximum positive vertical temperature gradient increases as the web thickness increase both at the top and the bottom surfaces. Similarly, the lateral temperature gradients across the webs increase as the web thickness increase.

8- Thin asphalt topping layers showed significant effects on the vertical positive temperature gradients. However, thicker layers of asphalt decreased the temperature of the top surface of concrete, which in turn led to lower vertical temperature gradients. The maximum vertical temperature gradients along the south web for topping thicknesses of 0, 50, 100, 150, and 200 *mm* were approximately 29, 34.4, 25.9, 20, and 15.8°C, respectively. On the other hand, the maximum positive lateral temperature gradients along the top slab for the same sequence of topping thicknesses were 6.8, 12.5, 11.2, 8.9, and 7.4°C, respectively.

11.1.3 The Analysis and Design of Thermal Actions in Turkey

The heat transfer finite element model was used in combination with long-term solar radiation and air temperature records of 10 Turkish cities from the seven regions of Turkey to propose design procedures for the temperature actions in concrete bridges in Turkey. The maximum positive and negative vertical temperature gradients in addition to the maximum and minimum mean temperatures of concrete box-girder bridges were considered. From this study, the following conclusions can be drawn:

1- Design gradient models were proposed for the positive and negative vertical temperature gradients along the depth of concrete bridge superstructures. The temperature at any part of the gradient models shall be calculated based on the top surface maximum positive temperature gradient (T). The top surface temperature gradient depends on the geographical location of the city. The maximum positive temperature gradient of the coastal regions of the Black Sea (Region 1) shall be taken as 26°C, while it shall be taken as 30°C for the rest of Turkey (Region 2). These values are considered for the case of no topping surface, adjustments shall be applied for different thicknesses of asphalt topping layer.

2- Along the depth of the superstructure (through the webs), the positive temperature gradient model composes of two parts. The first is a tri-linear distribution along the top 1.2 *m*, with a maximum temperature T at the top surface. The temperature decreases linearly from the top surface to a temperature of $0.3 T$ at 0.15 *m* below, then another line decreases down to 2°C along the next 0.25 *m*, followed by a third line that descends from 2°C to zero at 1.2 *m* below the top surface. The second part

is linear, which decreases from $0.2T$ at the bottom surface to the zero at a 0.2 m above.

3- The proposed negative gradient model along the depth the superstructure composes of two bilinear parts. The first extends along the upper 1.2 m of the superstructure, while the second extends along the lower 0.4 m of the superstructure. The maximum temperatures at the top surface and the bottom surface are $-0.4T$ and $-0.3T$. At 0.2 m from the top surface, the proposed temperature is $-0.2T$, while at 0.2 m from the bottom surface, it is $-0.1T$.

4- For concrete box girders, similar temperature gradient models were proposed across the top and bottom slabs above and below the box cavity and for both the positive and negative gradient cases. All of the proposed vertical temperature gradients showed good agreement with the distributions and values of the predicted maximum gradients.

5- Based on the proposed linear formulas of the daily maximum and minimum mean temperatures from the experimental work, and using long-term extreme maximum and minimum air temperatures of Turkey, the design maximum and minimum mean temperatures of concrete bridges shall be estimated and the longitudinal movements shall be calculated.

11.1.4 The Thermo-Mechanical Finite Element Analysis

Considering the recorded thermal conditions of Gaziantep in 2013-2014, and using the COMSOL finite element package by the coupling of the heat transfer and the solid mechanics modules, the thermal stresses and thermal deformations that arise from the effect of solar radiation and air temperature were analyzed for a simply supported concrete box-girded bridge. From this thermo-mechanical finite element analysis, the followings are concluded:

1- The thermal stress (tensile or compressive) and its value at any point in the cross-section depend mainly on the temperature distribution, hence the time of the day and of the year, and on the location of this point. On the exterior exposed surfaces, the stress is compressive during the day hours due to the positive temperature gradients that occur because of the heating of these surfaces, while it is tensile during the

night and the early morning due to the cooling of these surfaces, which results in negative temperature gradient. The behavior is the inverse for the interior surface points (inside the cavity) and the core points at the centroids of the slabs and the webs. In summer, for the exterior points on the top and bottom surfaces of the box-girder, the maximum compressive stress was recorded at the center of the top surface in 14-June at 12:00 PM and was -3.35 MPa , while the maximum tensile stress was 2.78 MPa , which was recorded at the southern corner of the top slab at 10:00 PM in 10-July. In 22-December, the maximum compressive and tensile stresses were -3.83 MPa and 1.14 MPa , which were recorded at the northern corners of the top and bottom slabs, respectively.

2- The vertical and lateral stress distributions along the slabs and the webs showed similar behaviors to their corresponding temperature distributions with minor differences but with reversed sign.

3- During the late night and early morning hours in summer, the vertical stress distribution starts with a region of sharp drop of the tensile stress from its maximum on the top surface to approximately zero near its mid thickness, from which a crescent region forms at which the stress reverses to compressive and then back to tensile. The same behavior is mirrored from the bottom surface and upward, however, the stress values are lower. A semi steady region with stress close to zero is formed between the top and bottom crescents along the interior depth of the web. In winter, the stress along the north web showed similar behavior to that of summer. On the other hand and along the south web, the stress continues decreasing from tensile at the top and bottom surfaces to maximum compressive at somewhere close to the mid height of the web.

4- During the hot hours (midday) and excluding the stress distribution along the south web in winter, which is affected by the concentrated lateral sunrays, the stress distributions along the south and north webs in summer and winter show approximately similar trend of variation along the depth, which is approximately the inverse of that at the early morning, with maximum compressive stresses at the surfaces and without the crescent region across the slabs. However, the stress along the interior depth of the web is more stable along the north web than along the south web.

5- The vertical displacement is almost identical for the central points at the top and bottom surfaces along the 24 hours of the day, while the corner points of the top and bottom slabs showed different behaviors of the lateral displacement along the 24 hours of the day. Moreover, the vertical displacements are high during summer due to the high positive temperature gradients and much lower in winter due to the low vertical temperature gradients. In contrary, the lateral displacements are higher in winter than in summer because of the higher lateral temperature gradients in winter. The maximum recorded vertical and lateral displacements in 14-June were approximately 12.5 and 1.2 *mm*, while they were 2.7 and 1.9 *mm* in 22-December.

11.2 Recommendations for Future Studies

Based on the literature survey and the results of the current study, the followings are recommended as required studies:

- 1- Studying the thermal actions in other types of bridges, such as steel, composite, and special superstructures considering the extreme weather conditions of Turkey to complete the proposed thermal actions provisions for bridge design in Turkey.
- 2- As concrete development continues, new concretes are introduced using new additives and new materials. The thermal properties of these concretes may noticeably changed, which may results in higher temperature gradients and hence higher thermal stresses and deformations. The studying of the effects of thermal properties of new concretes that may lead to higher solar absorptivity or lower thermal conductivity and specific heat is recommended.
- 3- As thermal environmental loads are repeated loads along the long live span of bridges, the investigation of the possible thermal fatigue stresses in combination with the creep from the static sustain loads is recommended.

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APPENDIX: SOLAR ANGLES

The quantity of solar radiation reaching any surface on the earth at any time depends on the location of this surface with respect to the sun. To correctly define this location, several basic and derived solar angles should be defined.

A.1 Basic Angles:

Basic angles are those angles that are related to the geographical location of the structure, the time of the day, and the day of the year.

1- The latitude L : It is location of any point on the surface of the earth with respect to the equator, which ranges from 0° to 90° for any point on the northern half of the earth, while it ranges from 0° to -90° for any point on the southern half of the earth.

2- The hour angle H : It is the angle that measures the inclination of sunrays at any time in the day based on the time of the solar noon of the day, which is also can be defined as the angle between sunrays at that time and the meridian passing the point. The hour angle is negative before solar noon and positive after solar noon, while it is zero at the solar noon of the day.

3- The declination angle D : It is a solar angle that measures the location of the sun with respect to earth for any day of the year, which is for any day is the angle between the sunrays at solar noon and the plane of the earth's equator. This angle is equal for all points on the earth's surface and is defined by the following equation in degrees:

$$D = 23.45 \sin \left[\frac{360}{365} (284 + n) \right] \quad \dots (A-1)$$

Where n is the day number from 1 for 1-January to 365 for 31-December.

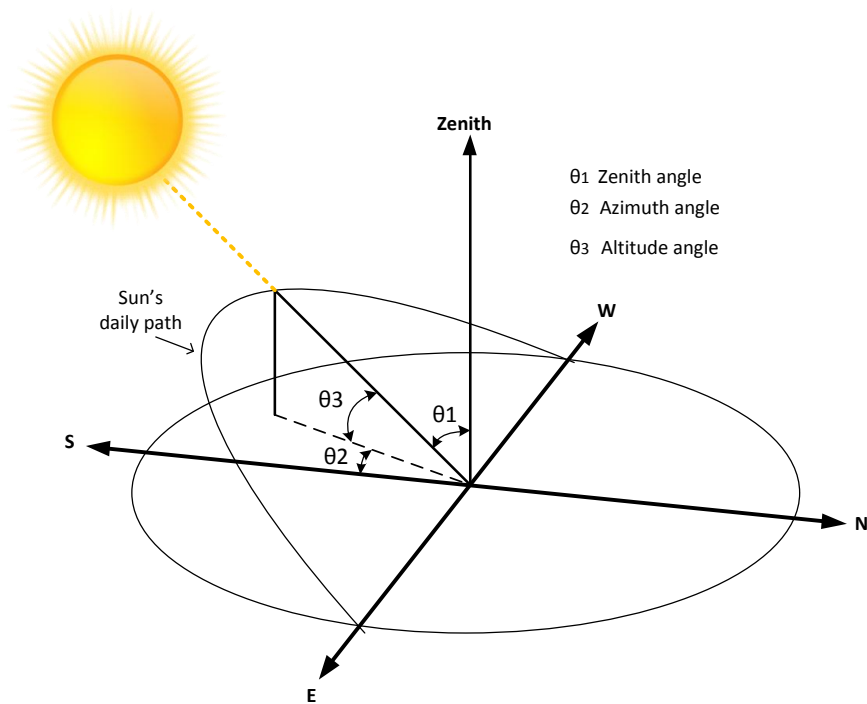


Figure A-1 Derived solar angles

A.2 Derived Angles:

To calculate the amount of solar incidence on any surface at any time, the following angles should be defined,

- 1- Solar zenith angle θ_1 : It is the angle between the zenith line (the directly overhead line) and the sunrays as shown in Figure A-1.
- 2- Solar azimuth angle θ_2 : It is the angle on the earth surface between the projection of sunrays and the due south as shown in Figure A-1.
- 3- Solar altitude angle θ_3 : It is the angle between the sunrays and the projection of sunrays on the earth surface, i.e. $\theta_3 = 90 - \theta_1$, as shown in Figure A-1.
- 4- Surface tilt angle δ : It is the angle measuring the inclination of the surface with the horizontal plane as shown in Figure A-2.
- 5- Solar incident angle θ : It is the angle between a line perpendicular to the surface and sunrays as shown in Figure A-2.

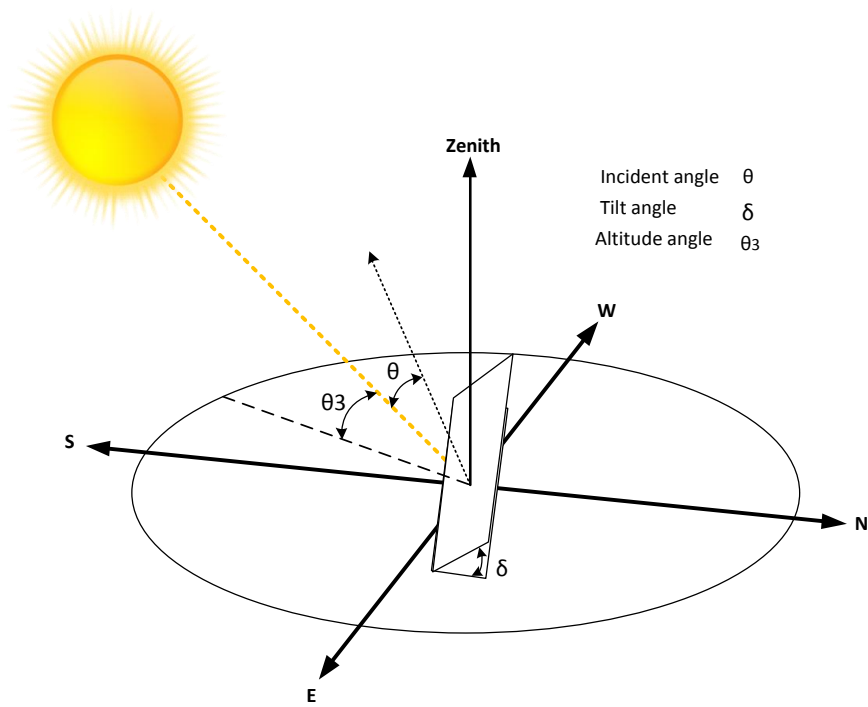


Figure A-2 The angles of an inclined surface