Finite element simulation of vertical temperature gradients in a standard W40×235 steel beam

Sallal R Abid*, Thaar S Al-Gasham
Civil Engineering Department, University of Wasit, Kut, Iraq

* Corresponding author: sallal@uowasit.edu.iq

Abstract. A finite element analysis was conducted in this research to understand the distribution of temperatures along with the depth of the standard steel W40×235 beam. The considered thermal loads were those of open environments, including the radiation of the sun and the temperature of the air in addition to wind movement. The thermal analysis considered the total solar radiation, ground reflected radiation, longwave radiation, mutual surface radiation and heat convection as the thermal boundary loads. The analysis was carried out for the experimentally recorded conditions of a sunny summer day. The results showed that the vertical temperature gradient approaches zero with stabilized beam temperature after midnight and up to the sunrise. On the other hand, the vertical temperature gradients at the top and bottom surfaces continuously increase with time reaching their maximum values at approximately 2:00 PM. The maximum temperature gradients at the top and bottom surfaces of the beam were 10.2 and 9.1 °C for the conditions of the investigated day.

Keywords: Finite element; thermal analysis; temperature; temperature gradient; steel beam

1. Introduction
The temperature gradient expression refers to the difference in temperature between two or more points along a specified path. In concrete sections, where the thickness of members is considerable and thermal conductivity is low, substantial temperature gradients between surface and section core form after high-temperature short-period heating of surfaces as in case of accidental fires [1-5], which leads to rapid deterioration of the material properties and structural performance [6-10]. On the other hand, long-term slow heating can also result in noticeable damages with time, especially if the surfaces are exposed to cycles of heating and cooling, as in the case of bridge superstructures [11-15]. In bridge girders, the temperature gradient is measured from the top surface, across the depth and reaching the girder’s soffit, which is termed as the vertical gradient. The focus of most of the research works is on the vertical gradient, both at the end of the cooling phase (maximum negative gradient) or during the noon hours (maximum positive gradient) [16-19]. The nonlinear vertical temperature gradient is the main source of thermal self-equilibrating stresses, especially in sections with considerable depths, which may be of high values that can cause concrete to crack [20-24]. In wide sections like box-girders, the lateral temperature gradient along the width of the girder or superstructure is also a serious impact on the long-term structural performance of the bridge [25-30]. Extensive experimental and fieldwork on temperature gradient effects on reinforced concrete and prestressed concrete girders were reviewed in the literature. On the other hand, steel girders are widely used in medium length superstructures, while the available research works on such types of girders are...
still much less than really required [31-37]. In this research, a finite element analysis was performed considering the influence of thermal loads of sun and atmospheric air on steel beams. The vertical temperature gradient in the steel beam was studied and verified using measurements from an experimental steel beam in summer.

2. The steel beam W40×235
The geometrical configuration and sectional dimensions of the standard W40×235 beam are shown in Figure 1. The beam has an overall depth of approximately 1008 mm and a flange width of approximately 302 mm, which means that it has a flange width-to-depth ratio of 0.3. The thicknesses of the flanges and web are approximately 40 and 21 mm, respectively, while its weight per unit length is approximately 350 kg/m. As the current analysis is a temperature analysis under environmental thermal loads, and as these loads are constant for all sections along a straight span, then there is no need to model the full length of the beam. Therefore, only a segment with 1000 mm length was modeled. To evaluate the investigated parameters, the temperatures at specific locations should be visualized; therefore, seven virtual thermocouples were distributed along with the depth of the beam from the top surface to the bottom surface. The thermocouple locations considered the thickness of the top and bottom flanges and the depth of the beam. The locations of the seven virtual thermocouples are listed in Table 1.

![Figure 1. Sectional dimensions of ASTM W40×235](image_url)

**Table 1. Sectional locations of virtual thermocouples**

| Virtual Thermocouple | x (mm) | y (mm) (height from bottom surface) | Location                        |
|----------------------|--------|-----------------------------------|---------------------------------|
| T1                   | 0      | 1008.4                            | Top surface                     |
| T2                   | 0      | 968.3                             | Bottom face of top flange       |
| T3                   | 0      | 808.4                             | 200 mm below top surface        |
| T4                   | 0      | 504.2                             | Mid-height                      |
| T5                   | 0      | 200                               | 200 mm above bottom surface     |
| T6                   | 0      | 40.1                              | Top face of bottom flange       |
| T7                   | 0      | 0                                 | Bottom surface                  |
3. Finite element modeling

The heat transfer through solid materials is controlled by the well-known thermal conduction formula, which is also termed as the Fourier heat differential equation. As shown in Equation 1, the thermal conduction, in terms of temperature variation with time, in any direction in the body is a function the thermal properties of the material. These controlling properties are the density of the material (ρ), which is constructional steel in this research, specific heat (C) and most importantly coefficient of thermal conductivity (k) [21].

\[ k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = \rho C_p \frac{\partial T}{\partial t} \] (1)

The thermal loads affecting the boundary surfaces of the steel beam are the same as those considered for thermal analysis of all members installed in open conditions. The solar radiation is mainly the temperature rising initiator and effective controller. The solar radiation reaches the surfaces is the net of direct, diffuse, and reflected radiations, which in some heat up the beam from sunrise to sunset. The effect on the different surfaces is variable based on many factors, including their inclination angles and shading influence of flanges on the web. The variation of air temperature is also a dominant influential factor on the heating and cooling process, which is included in both convection and longwave radiation processes. Where the body experiences a gradual loss of its heat after the heating phase by re-radiating the absorbed heat in terms of longwave radiation to the atmosphere.

On the other hand, the convection is the primary process of direct heat exchange between the beam surfaces and the surrounding air. Both the convection and longwave radiation are considered as the cooling processes. The formulation regarding the heat transfer process and the thermal loads on the beam surfaces is described in detail in previous researches [11, 16, 19]. The convection process takes place under the temperature difference of surface, and air temperatures, which is in the formulation should be multiplied by a convection coefficient (h). The convection coefficient is a function of wind speed and can be for the case of the current analysis calculated using Equation 2 [35].

\[ h = 5.6 + 4v \quad (v \leq 5 \text{ m/s}) \] (2)

The finite element thermal analysis was conducted in this research using the heat transfer module of COMSOL Multiphysics [38], as shown in Figure 2(a). This module has the capability to solve Equations 1 and apply all surface thermal loads discussed above. Tetrahedral elements were used to mesh the steel I-beam with triangular surface elements. The volume elements for temperature transfer were quadratic in order, while those of surface radiation were linear to optimize the calculation efforts and time. Totally, 7430 tetrahedral elements and 4970 triangular surface elements were built in the mesh of the conducted thermal analysis model of W40×235 as shown in Figure 2(b). The initial conditions were applied 48 hours before the starting hour of the analysis day to assure minimal effect of initial temperature on the obtained calculations. The thermal loads were applied exactly as obtained from an experimental weather station that includes air temperature, wind speed and solar radiation sensors. The current finite element thermal analysis was conducted for the thermal conditions of 14-June-2015, which were recorded for a steel girder in Gaziantep/Turkey. The reflected radiations on the vertical and horizontal surface, the hourly air temperature records and the wind speed variation with time were tabulated and uploaded to the conducted model as excel sheets. On the other hand, the geographical location, time and maximum daily solar radiation were defined in the COMSOL solar radiation model. A similar model of a steel beam was verified in a previous study with an experimental steel beam [35], which revealed accurate modeling with minor errors. Similarly, finite element analysis using the same program and same procedure for concrete [25, 28] and composite [19] girders were verified experimentally in other previous works and showed good simulation capability.
4. Temperature results

4.1. Temperature-time variation

As mentioned in the previous section, the analysis was conducted based on the thermal conditions of 14-June-2015, which are presented in a previous study [35]. For these conditions, the temperature analysis outputs were obtained for the virtual thermocouples T1 to T7 and discussed here. Figure 3 shows the temperature variation of five thermocouples with time for the 24 hours of the investigated day. T2 (lower face of the top flange) and T6 (upper face of the bottom flange) were not presented because their temperature was very close to those of T1 and T7, respectively. It should be reminded that these thermocouples are not surface thermocouples; they are located at the center of web thickness. It is evident in Figure 3 that the temperature T1 is the highest since just shortly after sunrise till approximate sunset, where it is the highest among all thermocouples from 7:00 AM to 6:00 PM. This result agrees with the natural movement of the sun in summer. Where the sun strikes surfaces from high inclination angles, which makes the radiations received by horizontal surfaces noticeably higher than those received by vertical surfaces. Consequently, the temperature of the top surface becomes higher than other thermocouples. Within the first shine hours (before 7:00 PM) and late shine hours (after 6:00 PM), the sun becomes very shallow in the horizon, where the top surface receives zero radiation. Hence, the temperature of the top surface is not the highest in such time periods. For the same reason, the web receives the total fraction of solar radiation in these times, which raises the temperature of the mid-depth thermocouple (T4) to becomes the one recording the highest temperatures, followed by T3 and T5 web thermocouples as shown in Figure 3.

Comparisons between the temperatures of the seven thermocouples at selected time steps (every four hours) are shown in Figure 4 as bar charts, which gives another picture of temperature variation from one location to another on the surface of the beam. It is obvious in the figure that during the night hours (midnight, 4:00 AM and 8:00 PM), the temperatures of the seven thermocouples is approximately equal. This can be attributed to three reasons; firstly, to the preceding cooling hours that stabilize the surface temperature close to air temperature, secondly to the high thermal conductivity of steel and thirdly to the small thin members of the steel beams. The late two reasons accelerate the stabilization of temperature between the surface and core temperatures. Consequently, the whole beam’s mass cools faster than in concrete sections. Therefore, the temperatures of inside and surface thermocouples read approximately equal temperatures. The slight decrease of web (T3, T4 and T5) temperatures in these times is due to their vertical configuration that allowed crossing wind path and hence experiencing slightly faster cooling.
4.2. Temperature gradients

The understanding of temperature gradient distributions is essential to understand the distribution of thermal stresses, along with the depth of the section. If the vertical distribution along the depth is linear, then no thermal stresses would be induced if the axial movement and rotation are allowed at supports. On the other hand, induced thermal stresses arise in the case of nonlinear vertical temperature gradient distributions regardless of end conditions. Figures 5 and 6 show explicitly that temperature gradients vary nonlinearly along with the depth of the beam section, which enforces the need for better understanding of these gradients. The temperature gradients shown in Figures 5(b) and 6(b) were calculated directly from the temperature distributions shown in Figures 5(a) and 6(a). The gradient calculation in this research was conducted by the simple subtraction of the beam’s minimum temperature at each time step from the temperatures of all other thermocouples; hence, the temperature gradient of the thermocouple with the lowest temperature becomes zero.

As shown in Figure 5(a), the temperature distributions during the night hours approximately vertical, which refers to a stabilized temperature, whereas shown in Figure 5(b), the temperature gradients are generally less than 2 °C. The highest temperature gradient in Figure 5(b) is shown to be at 8:00 PM,
which is still strongly affected by the daily temperature gradients with a higher top surface temperature. As the cooling hours becoming longer, the top surface temperature’s becomes approximately equal to the web temperature leading to lower temperature gradients, which is less than 0.5 °C at 2:00 AM and 5:00 AM. Just after sunrise, the web gets warmer quickly due to the concentration of inclined solar radiation leading to the temperature gradient shown at 6:00 AM in Figure 5(b).

![Figure 5](image)

**Figure 5.** Distributions of (a) temperatures and (b) temperature gradients during night hours

At 8:00 AM, the sun moves to higher altitudes in the sky, striking larger areas from the top surface and smaller area from the web, which in turn stabilizes the vertical temperature distribution and, consequently, gradient distribution, as shown in Figure 6. During the next hours, the sun keeps heating the horizontal surfaces leading clear positive temperature gradients till afternoon, with the highest gradients being recorded around 2:00 PM as shown in Figure 6(b). The maximum temperature gradient was 10.2 °C, which was recorded at 2:00 PM at the top surface. The gradient was decreasing nonlinearly down to the mid-depth of the beam, where it becomes zero. Then increase nonlinearly, reaching other maxima at bottom surface. The lower temperature along the top half of the web is attributed to the shading effect from the top flanges, while the high temperatures at the top surfaces can be attributed to direct radiation from sun at its top surface and grounds reflected radiation at its bottom surface.
5. Conclusions

Based on the finite element analysis of the thermal budget of the standard W40×235 steel beam under the direct influence of thermal loads from sun and air, the temperatures at different locations were analyzed, and the temperature gradient was investigated. The most important conclusions of this numerical investigation can be summarized as follows:

- The beam is almost thermally stabilized since after midnight to just before sunrise with approximately equal temperatures at all parts. This attributed to the high thermal conductivity of the steel and the thin members of the beam that allowed for quick cooling across the thickness of its flanges and web.
- The temperature gradients during the day were nonlinearly distributed along with its depth of the beam with the highest temperatures at the top surface a zero temperature gradient at the mid-depth of the beams section. For the investigated day, the maximum temperature gradient was recorded at 2:00 PM and was 10.2 °C.
- The temperatures at the beam’s bottom surface were also high at noon hours due to the direct solar radiations on the top surface of the bottom flange and the reflected radiations from the ground at its bottom surface. At 2:00 PM, the recorded temperature gradient at the bottom surface was 9.1 °C.

6. References

[1] Zhang P, Kang L, Wang J, Guo J, Hu S and Ling Y (2020) Mechanical Properties and Explosive Spalling Behavior of Steel-Fiber-Reinforced Concrete Exposed to High Temperature—A Review. *Appl. Sci.*, 10, 2324.

[2] Le Q X, Dao V T N, Torero J L, Maluk C and Bisby L (2018) Effects of temperature and temperature gradient on concrete performance at elevated temperatures. *Adv. Struct. Eng.*, 21, 1223–1233.

[3] Al-Owaisy S R, Shallal M A (2007) Strength and elasticity of steel fiber reinforced concrete at high temperatures. *J. Eng. Sustain. Develop.*, 11(2), 125-133.

[4] Xie Q, Zhang L, Yin S, Zhang B and Wu Y (2019) Effects of High Temperatures on the Physical and Mechanical Properties of Carbonated Ordinary Concrete. *Adv. Mater. Sci. Eng.*, 2019, 5753232. Wu H, Lin X, Zhou A (2020) A review of mechanical properties of fibre reinforced concrete at elevated temperatures. *Cem. Con. Res.*, 135, 106117.

[5] Al-Gasham T S, Mhalhal J M, Jabir H A (2019) Influence of post-heating on the behavior of reinforced self-compacting concrete hollow columns. *Eng. Struct.*, 22, 266-277.
[6] Al-Owaisy S R (2006) Post heat exposure properties of steel fiber reinforced concrete. J. Eng. Sustain. Develop., 10(2), 194-207.

[7] Arna’ot F H, Abbass A A, Abualtemen A A, Abid S R, Özakça M (2017) Residual strength of high strength concentric column-SFRC flat plate exposed to high temperatures. Constr. Build. Mater., 154, 204-218.

[8] Arna’ot F H, Abid S R, Özakça M Tayşi N (2017) Review of concrete flat plate-column assemblies under fire conditions. Fire Saf. J., 93, 39-52.

[9] Al-Owaisy S R (2007) Effect of high temperatures on shear transfer strength of concrete. J. Eng. Sustain. Develop., 11(1), 92-103.

[10] Hagedorn R, Marti-Vargas J R, Dang C N, Hale W M, Floyd R W (2019) Temperature gradients in bridge concrete I-girders under heat wave. J. Bridge Eng., 24(8), 1-14.

[11] Abid S R (2018) Three-dimensional finite element temperature gradient analysis in concrete bridge girders subjected to environmental thermal loads. Cogent Eng., 5(1), 1-15.

[12] Lu H, Hao J, Zhong J, Wang Y, Yang H (2020) Analysis of sunshine temperature field of steel box-girder based on monitoring data. Adv. Civ. Eng., 2020, 1-10.

[13] Rojas E (2014) Uniform temperature predictions and and temperature gradient Effects I-girder and box girder concrete bridges. M.Sc. Thesis. Utah State University, USA.

[14] Zhao L, Zhou L-Y, Zhang G-C, Wei T-Y, Mahunon A D, Jiang L-Q, Zhang Y-Y (2020) Experimental study of the temperature distribution in CRTS-II ballastless tracks on a high-speed railway bridge. Appl. Sci., 10(6), 1980.

[15] Abid S.R., Tayşi N., Özakça M. (2014). Experimental measurements on temperature gradients in concrete box-girder bridge under environmental thermal loads, In Proceedings of the Istanbul Bridge Conference, Istanbul, Turkey. 1-14.

[16] Abid S.R., Abbass A.A., Alhatmey I.A. (2019). Seasonal temperature gradient distributions in concrete bridge girders: A finite element study, In Proceedings of 2019 Developments in eSystems Engineering (DeSE), Kazan, Russia, 374-379.

[17] Mussa, F., Abid, S.R., Tayşi, N. (2020). Winter Temperature Measurements in a Composite Girder Segment, IOP Conf. Ser.: Mater. Sci. Eng., 888, 012074.

[18] Liu J, Liu Y, Jiang L, Zhang N (2019) Long-term field test of temperature gradients on the composite girder of a long-span cable-style bridge. Adv. Struct. Eng., 22(13), 1-14.

[19] Abid S R, Mussa F, Tayşi N, Özakça M (2018) Experimental and finite element investigation of temperature distributions in concrete-encased steel girders. Struct. Control Health Monit., 25(1), 1-23.

[20] Elbadry M, Ghali, A (1986) Thermal stresses and cracking of concrete bridges. ACI J., 83, 1001-1009.

[21] Ghali A, Favre R, Elbadry M (2002) Concrete Structures: Stresses and Deformation. 3rd Edition, London: E & FN Spon.

[22] Abid S R, Tayşi N, Özakça M (2016) Experimental analysis of temperature gradients in concrete box girders. Constr. Build. Mater., 106, 523-532.

[23] Nasr A, Kjellstrom E, Bjornsson I, Honfi D, Ivanov OL, Johansson J (2020) Bridges in a changing climate: a study of the potential impacts of climate change on bridges and their adaptations. Struct. Infrastruct. Eng., 16(4), 738-749.

[24] Gottsater E., Ivanov L (2019) Spatial temperature differences in portal frame bridges. Struct. Eng. Int., 30(2), 1-8.

[25] Tayşi N, Abid S R (2015) Temperature distributions and variations in concrete box-girder bridges: experimental and finite element parametric studies. Adv. Struct. Eng., 18(4), 469-486.

[26] Lin J, Xue J, Briseghella B, Xue J, Tabatabai H, Huang F, Chen B (2020) Temperature monitoring and response of deck-extension side-by-side box-girder bridges, J. Perform. Constr. Facil., 34(2), 04019122.

[27] Song Z, Xiao J, Shen L (2012) On temperature gradients in high-performance concrete box girder under solar radiation. Adv. Struct. Eng., 15(3), 399-415.
[28] Abid S R, Tayşi N, Özakça M (2014) Three-dimensional thermal modeling of temperature variation in concrete box-girders using COMSOL. In proceedings of the 2014 COMSOL conference in Cambridge, Cambridge, UK, 1-5.

[29] Gu B, Chen Z, Chen X (2014) Temperature gradients in concrete box girder bridge under effect of cold wave. J. Cent. South Univ., 21, 1227-1241.

[30] Abid S R, Tayşi N, Özakça M (2020) Temperature Records in Concrete Box-Girder Segment Subjected to Solar Radiation and Air Temperature Changes. IOP Conf. Ser.: Mater. Sci. Eng., 870, 012074.

[31] Wang Y, Shi Y, Lin C (2010) Experimental study on the temperature of steel members in sunshine. J. Build. Struct., 31, 140-147.

[32] Liu H, Chen Z, Zhou T (2012) Numerical and experimental investigation on the temperature distribution of steel tubes under solar radiation. Struct. Eng. Mech., 43(6), 725-737.

[33] Liu H, Chen Z, Zhou T (2012) Theoretical and experimental study on the temperature distribution of H-shaped steel members under solar radiation. Appl. Therm. Eng., 37, 329-335.

[34] Chen D, Wang H, Qian H, Li X, Fan F, Shen S (2017) Experimental and numerical investigation of temperature effects on steel members due to solar radiation. Appl. Therm. Eng., 127, 696-704.

[35] Abid S R (2020) Temperature variation in steel beams subjected to thermal loads. Steel Compos. Struct., 34(6), 819-835.

[36] Xue J, Lin J, Briseghella B, Tabatabai H, Chen B (2020) Solar radiation parameters for assessing temperature distributions on bridge cross-sections. Appl. Sci., 8, 627.

[37] Zhang C, Liu Y, Liu J, Yuan Z, Zhang G, Ma Z (2020) Validation of long-term temperature simulations in a steel-concrete composite girder. Struct., 27, 1962-1976.

[38] COMSOL Multiphysics v 4.3. (2012), COMSOL Multiphysics User’s Guide, Stockholm, Sweden.