Prediction of the maximum temperature of steel I-beam under the effect of environment parameters

Sallal R Abid1*, Hussein Al-Bugharbee2
1Civil Engineering Department, University of Wasit, Kut, Iraq
2Mechanical Engineering Department, University of Wasit, Kut, Iraq

* Corresponding author: sallal@uowasit.edu.iq

Abstract. In this work, prediction of the maximum temperature in steel beam is investigated under the effects of the atmospheric thermal loads. The current work presents a nonlinear formula that relates the steel beam maximum temperature to the solar radiation, air temperature and wind speed. The datasets were obtained experimentally from an I-section steel beam that was installed in the field. The data cover the surface temperature at different locations on the beam section, air temperature, solar radiation and wind speed, which were recorded over 21 summer days. Two different correlation formulas were introduced and their performance was compared. Based on the results obtained in this study, the beam maximum temperature can be predicted accurately with a correlation coefficient of approximately 0.94 from solar radiation, air temperature, wind speed and their duplicates.

Keywords: steel beam; solar radiation; temperature; wind speed; nonlinear regression.

1. Introduction
Temperatures are known to of detrimental effect on structural materials and structural members. Exposing a structural material to elevated temperatures for short periods, as in accidental fires, can be very harmful. The material microstructure can severely be affected leading to the drop of its mechanical properties and durability [1-4]. Moreover, the structural performance of exposed member can noticeably be degraded [5-8]. The exposure to temperature fluctuations for long periods can also affect the structural performance even if these temperatures do not exceed 50 °C. Several important structures like bridges are being exposed to atmosphere during their entire live. The temperature of the surrounding air and the direct, diffuse or reflected radiations from the sun are inconstant during the day hours, from day to another and from season to another. As these are the major provenance of atmospheric heat, the temperatures of naked structural members of bridges and other structures are of non-stop alteration. Previous studies showed that temperature fluctuation due to atmospheric loads can impose significant stresses in bridge girders [9-11]. The induced stresses were measured to be as high as those due the overall dead load of the superstructure, which can even leads to distinguished cracking of concrete [9, 12]. The cracking is known to reduce the lifespan by impacting the durability of the material. To reduce this effect,
two main issues must be considered. The first is the diurnal and seasonal changes of the overall temperature of the member, which control the expansion and contraction of the superstructure. This temperature is evaluated using the mean temperature of the bridge. The second issue is the distribution of temperatures in the sectional area of the member, which induce temperature gradients along the depth of the superstructure. This gradient is responsible of the unfavorable self-equilibrating stresses. In specific types of deep or cellular structures, self-equilibrating stresses can be of a major concern [9, 12-15].

The temperature alteration was recognized as one of the major loads of bridges by many bridge design practice codes. Because of the importance of this issue, several recent researches were conducted to investigate the effect of atmospheric thermal loads on steel [16-20], composite [21-23] and concrete bridge superstructures and scaled members [24-32]. Field, experimental and numerical investigations focused during the last few years on prediction of temperatures and temperature variation of members affected by solar radiation and wind speed. Although of the plenty of research in this field, few researches were found in literature on the sole effect of atmospheric loads on steel members [33-36]. Aiming to enrich the knowledge in this corner, a steel beam was fabricated in this study and exposed to open atmosphere to evaluate its temperature variation under atmospheric thermal load’s influence. Based on the temperature records obtained from the continuous measurements, nonlinear correlations were introduced to predict the influential temperatures of steel beams.

2. Experimental work
To evaluate the thermal response of structural steel members in open areas, a prismatic steel beam was fabricated and installed in direct and continuous touch with atmospheric loads. The configuration and geometrical details of the steel beam are shown in Figure 1, while Figure 2 shows a photo of the experimental steel beam. Because atmospheric thermal loads are constant at each time for prismatic members with straight axis, the length of the beam is of negligible effect on its temperature analysis. Therefore, 500 mm length segment was fabricated for this purpose. As the main aim of this research is to evaluate the variation of its temperature with time, surface temperature sensors were installed at different locations. The sensors were type T thermocouples and were installed in a distribution that allows for considering the effect of beam configuration on its temperature. As shown in Figs. 1 and 2, the beam has a typical I-shape with two identical flanges of 200 mm width and a central web. The flange overhanging wings affects the web temperature. This effect comes from the shading of a part of the web by crossing the path of solar radiation, which depends mainly on the time and sun movement. To cover the shading effect, three thermocouples were installed along the web depth; two close to the top and bottom flanges and one mid-depth thermocouple. These thermocouples are denoted as TC3, TC4 and TC5 from top to bottom with distances from top and bottom surfaces as shown in Figure 1.
The thermocouple TC1 on the top surfaces is installed where the maximum solar radiation amount is received during the hot season, while the bottom surface's thermocouple (TC7) is installed where the maximum reflected radiation from the ground is received. The thermocouples TC1 and TC7 which were installed along the central vertical axis of web, while the thermocouples TC2 and TC6 were installed away from the web on the bottom surface of the top flange and top surface of the bottom flange, respectively, as shown in Figure 1. It should be noticed that except TC1 and TC7, all other thermocouples were installed on the northern side of the beam.

In addition to the temperature sensors, three other sensors were installed in the experimental area to measure air temperature, solar radiation, and wind speed, which are shown in Figure 2. These three sensors in addition to the data acquisition system were supplied by Campbell Scientific. The measurements of air temperature, solar radiation, wind speed, and steel beam temperature were recorded by the data acquisition system at time intervals of half an hour, which means that there were 480 data records every day. As the data measurements were continued for 21 days, the total obtained records were 10080, with 1008 records for each of the ten environmental and temperature sensors.

3. Multivariate nonlinear modeling

In this section, the proposed methodology of correlating the environmental thermal load and the beam maximum temperature is presented. The principles of extraction of correlation formula contain the following three steps:

a. A suitable correlation formula is assumed. This formula relates the dependent variables \((x_1, x_2, x_3 \text{ and } x_n)\) (i.e. environmental thermal loads) to the independent variable \((y)\) (i.e. maximum temperature of beam).

b. An initial set of coefficients that weights the dependent variables are assumed.
c. A suitable algorithm for estimating the best set of coefficients that provides the minimum error between a predicted independent variable \((y_p)\) and the real independent variable \((y)\).

To evaluate the prediction accuracy of the model, the following metrics are used:

\[
MSE = \frac{1}{N} \sum_{i=1}^{N} (y_{pi} - y_i)^2 \\
MAE = \frac{1}{N} \sum_{i=1}^{N} |y_{pi} - y_i| \\
R = \frac{\sum_{i=1}^{N}(y_{pi} - y_{p})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(y_{pi} - y_{p})^2} \sqrt{\sum_{i=1}^{N}(y_i - \bar{y})^2}}
\]  

(1) (2) (3)

Where \(MSE\) is the mean square error, \(N\) is the number of readings, \(y_{pi}\) is the \(i^{th}\) predicted value, \(\bar{y}_p\) is the mean of predicted values, \(\bar{y}\) is the mean of measured values, \(y\) is the measured value, \(MAE\) is the mean absolute error and \(R\) is the correlation coefficient.

4. Atmospheric Thermal Measurements

To adequately analyze the temperature distribution in any structural member under atmospheric loads effect, these loads must be well understood. The variations of air temperature, solar radiation and wind speed with time are the key influential parameters in such an analysis. In this research, the temperature analysis of steel beams is the study target. The beam was kept in the study field for 21 summer days in June. The reads from the surface steel thermocouples and those from weather station sensors were recorded and collected simultaneously. As it is known, solar radiation is zero during the night hours, while it increases continuously from morning to noon, reaching maximum values close to midday. Then after, it drops continuously until sunset, where its value approaches zero. The same behavior was recorded in this study for all sunny days, while some temporary fluctuations were noticed in the existence of a cloud cover. Figure 3 shows the solar radiation recorded in this study along an arbitrary sunny day (10-June) in this study, which reflects the typical behavior discussed above. The figure also shows that air temperature decreases during the night hours reaching its minimum before sunrise then increases until the daily maximum temperature plateau between 12:00 and 4:00 PM. As the daily heating decreases due the dropping of solar radiation, air temperature also decreases noticeably along the rest shining hours and night hours. The wind speed variation has no specific trend as those of air temperature or solar radiation. Instead, a random wind speed variation was recorded for each of the tested days as shown in Figure 4.

![Figure 3](image-url)

Figure 3. Typical air temperature and solar radiation variation in a sunny summer day
Figure 4. Wind speed variation in the selected day

5. Maximum Temperature Correlations

It was noticed that there were some efforts in the literature [18, 35] to correlate the bridge influential temperatures with the atmospheric parameters to present acceptable prediction formulas. In this study, the maximum temperature ($T_{\text{max}}$) of the bridge is correlated to the effective thermal parameters in open environments. Figure 5 shows the linear relations between the maximum temperature of the beams and each of the three environmental parameters. It is obvious the bridge maximum temperature shows some sort of linear trend with air temperature but with low determination coefficient ($R^2$) of approximately 0.61. Similarly, the relation with solar radiation during the shining hours resulted in $R^2$ of approximately 0.56. On the other hand, the wind speed shows no specific trend with $T_{\text{max}}$, which reflects its negligible effect on the maximum temperature compared to the effects of air temperature and wind speed.

![Figure 5](image-url)
As it is discussed in the Figure 5, it is not accurate to consider only one environmental parameter to determine the maximum temperature of the beam. Similarly, it was found that linear relations are not adequate for such a purpose in this study. Therefore, nonlinear multivariate regression is considered in this study to predict $T_{\text{max}}$ from the environmental thermal loads. Two correlation formulas were obtained in this study. Both of them have the general nonlinear structure shown in Equation (4) as it gives more flexibility in the prediction process.

$$y = c_0 + \sum c_i x_i^{c_i+1}$$  \hspace{1cm} (4)

The first formula correlates the solar radiation ($SR$), air temperature ($T_{\text{air}}$) and squared solar radiation ($S$) to the beam maximum temperature ($T_{\text{max}}$) as in Equation (5).

$$T_{\text{max}} = c_0 + c_1 \cdot SR^{c_2} + c_3 \cdot T_{\text{air}}^{c_4} + c_5 S^{c_6}$$  \hspace{1cm} (5)

The model coefficients are presented in Table 1.
Table 1. Model coefficients of Equation (5)

| $c_0$  | $c_1$  | $c_2$  | $c_3$  | $c_4$  | $c_5$  | $c_6$  |
|--------|--------|--------|--------|--------|--------|--------|
| -34.9744 | 0.1628 | 0.9889 | 26.6617 | 0.3071 | -0.2744 | 0.4550 |

The second formula considers the influence of wind speed (i.e. the square term of wind speed) as in Equation (6):

$$T_{\text{max}} = c_0 + c_1 \cdot S + c_2 \cdot C^3 + c_3 \cdot \frac{T_{\text{air}}^{c_4}}{S} + c_5 \cdot S^{c_7} + c_6 \cdot W^9$$

(6)

Where $W_s$ is the square of wind speed. The results of the correlation can be seen in Table 2

| $c_0$  | $c_1$  | $c_2$  | $c_3$  | $c_4$  | $c_5$  | $c_6$  | $c_7$  | $c_8$  |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| -3.0959 | 0.3812 | 0.7089 | 9.2789 | 0.5010 | -1.8739 | 0.2388 | -2.1394 | 0.4889 |

The performance of the model is measured by mean square error ($MSE$), mean absolute error ($MAE$), correlation coefficient ($R$) and determination coefficient ($R^2$) which are described previously in section 3. Table 3 compares the evaluation metric for the two formulas. From the table, the prediction relationship shows acceptable accuracy where $R^2=0.93$, $MAE=3.77$ °C. However, the other prediction formal shows less accurate performance when compared to the first formula one. This improvement of the model performance can be attributed to the incorporation of the effect of the wind speed on the $T_{\text{max}}$.

Table 3. Evaluation metrics of the two prediction formulas

|                | Formula 1 |          |          |          | Formula 2 |          |          |
|----------------|-----------|----------|----------|----------|-----------|----------|----------|
| $MSE$          | 0.04      | 0.078    |          |          |           | 0.078    |          |
| $MAE$          | 4.79      | 3.77     |          |          | 4.79      | 3.77     |          |
| $R$            | 0.89      | 0.94     | 0.80     | 0.87     | 0.80      | 0.87     | 0.89     |
| $R^2$          | 0.80      | 0.87     | 0.87     | 0.87     | 0.87      | 0.87     |          |

Figure 6 illustrates the distinction between the predicted and experimental values of $T_{\text{max}}$. It can be noticed that the second formula succeeds in decreasing the differences between the predicted and experimental data particularly at the peaks value. As it was mentioned that the absolute difference is 3.77 °C in average, while that of the first formula is approximately 4.79 °C. Similarly, the correlation and determinations coefficients of the second formula are distinguishably better than the first one. This means that although the linear regression showed minor effect of wind speed on the beam maximum temperature, it resulted in more accurate nonlinear formula when combined with the other parameters. The data points represent the number of readings

![Figure 6](image-url)

Figure 6. Predicted and the experimental $T_{\text{max}}$ (a) formula 1 (b) formula 2
Figure 6 illustrates the distinction between the predicted and experimental values of $T_{\text{max}}$. It can be noticed that the second formula succeeds in decreasing the differences between the predicted and experimental data particularly at the peaks value. As it was mentioned that the absolute difference is $3.767^\circ\text{C}$ in average, while that of the first formula is approximately 4.8. Similarly, the correlation and determinations coefficients of the second formula are distinguishably better than the first one. This means that although the linear regression showed minor effect of wind speed on the beam maximum temperature, it resulted in more accurate nonlinear formula when combined with the other parameters. The data points represent the number of readings.

6. Conclusion

This study investigates the possibility of correlating the environmental thermal loads to the maximum temperature of steel beams. An I-steel beam was fabricated and kept in an open environment for 21 continuous days. The beam was instrumented with several thermocouples in addition to a weather station that include solar radiation, air temperature and wind speed sensors. Based on the collected temperature measurements from the thermocouples installed on the surfaces of flanges and web of the beam, the following conclusions were obtained.

- The solar radiation can be weakly linearly correlated to the maximum surface temperature of the beam, while the linear correlation between air temperature and beams maximum temperature was slightly better, but still inadequate for prediction purposes where the determination coefficient was approximately 0.61.
- The wind speed showed no distinguishable trend of correlation with the maximum surface temperature of the steel beam.
- The beam maximum temperature can be related nonlinearly with the three controlling environmental loads of air temperature and solar radiation with good determination coefficient, while including the wind speed led to a more accurate formula, which is more precise in predicting the beam maximum temperature with $R=0.94$ and $\text{MAE}=3.77^\circ\text{C}$.

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