Experimental records based-simplified modeling of mean temperatures of steel beams in open environment

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. Solar radiation and air temperature hourly, daily and seasonally variation is of a noticeable impact on bridge girders and other exposed structures. The time-dependent changing of the mean temperature of the girder and the complete superstructure is the key parameter to calculate support movements and rotations. Based on an experimental measurement from a steel beam installed in an open environment, the mean temperature variation of steel beams could be studied and modeled in this investigation. The experimental records included steel temperatures of web and flanges, solar radiation and air temperature and speed. The recorded thermal measurements were used to obtain correlation relationships that describe the mean temperatures of the web, flanges and the whole beam in terms of wind speed, air temperature and solar radiation. These correlation relationships were validated using a part of the experimental data. The results showed that predicted models has good correlation coefficients.

Keywords: prediction model; environment thermal load; flange temperature; solar radiation; steel beam.

1. Introduction
The deterioration of material properties and structural performance after elevated temperature exposure became a distinguished issue [1-8]. On the other hand, the long-term exposure to temperature variation is also of unfavorable impact. Such case of loading is dominant for structures held in naked environment. Examples of such structures are the electrical and communications towers, on-ground and elevated storage tanks, irrigation flumes especially elevated ones and most importantly bridge structures. In addition to their standard design dead, live, moving, fluid and wind loads, these structures are subjected to thermal loads that arise mainly from solar radiation. Namely, three types of environmental thermal loads control the heating and cooling, and thus temperature fluctuation, of the exposed elements of bridge structures. The first is the solar radiation, which reaches the surfaces either by direct rays from the sun across the atmosphere or by means of diffuse radiation from clouds and other pollutants in the sky. The radiation from the sun can also reach the lower and inclined surfaces by the virtue of reflections from ground and surroundings [9, 10]. The second major environmental load is the temperature of the surrounding ambient air, which is worms up during the day time and cools down during the night time, leading to the increase and decrease of surface temperatures of the structure via thermal convection, which is also controlled by the speed of air (wind speed).
With time, the long-term temperature rise and drop of surface temperature of exposed structures, would lead to unwanted durability issues that induce the periodical need of expensive maintenance. In the case of bridge superstructures, damages of expansion joints and bearing plates are among the consequences of the increasing and decreasing of the superstructure’s mean temperature. On the other hand, several sectional and longitudinal cracking patterns can be attributed to thermal effects including the induced self-equilibrating stresses that arise from sectional temperature gradients [12, 13]. Such distinguished cracking and high stresses were reported by previous studies [14-16]. To eliminate, or at least, to reduce the unwanted consequences of temperature variations due to solar radiation and air temperature, adequate design that is based on well-knowledge about thermal loads effects and the resulted temperature distributions is of a priority importance.

Several previous researches [17-25] were conducted on reinforced concrete or prestressed concrete bridge superstructures and girders with the main focus being the temperature and thermal stress distributions. Similarly, the literatures shows that adequate quantity of information about this issue was provided on steel-concrete composite girders by other research works [26-30]. Three types of research works are available in the literature, which are field studies including the instrumentation of existing bridges, experimental studies on full-scale or scaled girder segments and numerical studies, especially using the finite element method [24, 31]. Many of these studies tried to introduced experimental-based temperature gradient models along the vertical axis of the girder, and in the case of box-girders, along the lateral axis also [12, 14-16]. Other research works focused on the stress distributions due to thermal loads, while a third group of research works tried to present simplified analytical formulas to predict key temperatures like maximum, and mean temperatures or maximum temperature gradient.

According to the literature survey conducted in this research, few research works were found on pure steel members tested under direct exposure to open atmospheric conditions [11, 32-36]. Furthermore, only a very limited number of published articles are available on the thermal analysis of steel beams under environmental thermal loads effects. As a trial to fill a side of this gap of knowledge, the experimental temperature variation response of steel beams was investigated in this research. Based on the experimental summer records, model formulas were introduced to better simplify the estimation of mean temperatures in I-type steel beams.

2. Experimental work
The experimental work of this research includes the fabrication and instrumentation of an I-shape steel beam segment. The beam is composed of three steel plates with 8 mm thickness and length of 500 mm. This length is the span of the beam segment, which was limited to 500 mm because of the prismatic configuration of the section. Such configuration results in equal sectional distribution of thermal loads along the span but of course variable with time. On the other hand, the width of the top and bottom flange plates was 200 mm, while the depth of the web plate was 484 mm so that the total depth of the beam became 500 mm.
Figure 1 shows the sectional configuration and dimensions of the experimental steel I-beam and its length. The steel beam was kept freely resting on thermally-isolated wood blocks as shown in Figure 2 in an open field, which assures that there are no close buildings or objects that would affect the atmospheric heat transfer process via shading leverage.

As the main aim of this research is to analyze the impact of atmospheric thermal loads on the temperature of steel beams, thus, temperature sensors are required to measure the variation of the surface temperature. Therefore, seven thermocouples were distributed on the surfaces of the flanges and web of the beam as shown in Figure 2. The sensors were distributed so that the temperatures of the flanges top and bottom surfaces in addition to the web can be captured. The thermocouples were numbered from TC1 to TC7 from the top surface down to the bottom surface, respectively. TC1 was installed on top surface, TC3 and TC5 were installed on the side surface of the web 30 mm from the top and bottom flanges, respectively, while TC4 was the web mid-depth thermocouple. TC2 was installed at the bottom face of the top flange 20 mm away from the edge, while TC6 was installed on similar location on the top face of the bottom flange. Finally, TC7 was installed at the center of the bottom surface of the beam. Moreover, other sensors are required to measure the atmospheric thermal
loads that control the thermal budget of the beam. These sensors should measure the time-dependent variation of ambient air temperature of the experimental field, the total solar radiation received by horizontal surfaces on the ground and the speed of the surrounding air. Therefore, air temperature probe and a silicon pyranometer were installed to measure the variation of air temperature and solar radiation, while a three-cup anemometer was the used wind speed sensor. The ten sensors were connected to a Campbell CR1000 data logger, which was programmed to collect measurements from all sensors each 30 minutes.

3. Correlation relationships
Finding of correlation relationships for multivariate modelling is a challengeable task. This is because the selection of correlation formula as well as the independent variables and their weights cannot be conducted directly. Model complexity is not preferable always unless there is a necessity for it. In the present study, linear formulas are adopted in order to keep the simplicity whenever it is possible. The linear prediction model has the following expression:

\[ y_p(i) = c_o + c_1 \cdot x_1(i) + c_2 \cdot x_2(i) + \cdots + c_n \cdot x_n(i) \]  

Where 

\( y_p(i) \) is the dependent variable of the \( i^{th} \) observation, \( x_j(i) \) is the \( j^{th} \) independent variable of the \( i^{th} \) observation and \( j=0, 1, 2 \ldots n \), where \( n \) is the number of independent variables. \( c_j \) is the coefficients of the prediction model to model validation training and test. The following metrics are used for estimating the prediction error.

\[ MAE = \frac{1}{N} \sum_{i=1}^{N} (y_p(i) - y(i)) \]  

\[ NMSE = 1 - \frac{\sum_{i=1}^{N} (y_p(i) - y(i))^2}{\sum_{i=1}^{N} (y(i) - \bar{y})^2} \]  

\[ R = \frac{\sum_{i=1}^{N} (y_p(i) - \bar{y_p})(y(i) - \bar{y})}{\sqrt{\sum_{i=1}^{N} (y_p(i) - \bar{y_p})^2 \sum_{i=1}^{N} (y(i) - \bar{y})^2}} \]  

Where \( MAE \) is mean absolute error and \( R \) is coefficients of correlation, \( y(i) \) the \( i^{th} \) experimental observation, \( \bar{y} \) the average value of the experimental readings, \( \bar{y_p} \) the average value of the predicted readings.
4. Results and discussion

4.1. Preparation of dependent variables
In the current work, four models are identified for predicting the following variables; (1) beam section mean temperatures $T_m$, (2) beam web mean temperature $T_w$, (3) upper flange mean temperature $T_{uf}$ and (4) lower flange mean temperature $T_{lf}$. These variables are computed from multiplication of the thermocouple readings located on them by the Area.

4.2. Model formulation
Considering the simplicity of the model, a linear formula is made to describe the relationship of each of the above dependent variables to the environment thermal load. The form of these models and their coefficients are described in below:

\[
T_m = 8.743 - 2.144W_S + 0.0078T_{air} + 0.9789SR
\]

\[
T_w = c_{w0} + c_{w1}W_S + c_{w2}T_{air} + c_{w3}SR
\]

\[
T_{uf} = c_{uf0} + c_{uf1}W_S + c_{uf2}T_{air} + c_{uf3}SR
\]

\[
T_{lf} = c_{lf0} + c_{lf1}W_S + c_{lf2}T_{air} + c_{lf3}SR
\]

4.3. Model validation

Figure 3. Probability distribution of residuals, A) $T_m$ model B) $T_w$ model C) $T_{uf}$ model and D) $T_{lf}$ model
In this study, and for the purpose for investigating the model accuracy of prediction, the experimental are divided into 70% as a training sample (367 readings) and 30% (157 readings) as testing sample. The training sample is selected to build the linear multivariate regression models while the testing sample is used to validate those models. The Table 1 shows the normalized mean square error (NMSE) for the four models in predicting the training samples. Over all, the model accuracy ranges from 0.898 to 0.920 which are accepted. Figures 3, A-D shows the normal distribution of the residuals obtained from the prediction model. The probability distribution of the residuals shows the presence of some outliers in readings. These outliers have not always be removed as they might contain important information. It is also observed from the figures that majority of the data follows a normal distribution.

### Table 1. Normalized mean square error for prediction of training and testing samples

| Model | Training | Testing |
|-------|----------|---------|
| $T_m$ | 0.920    | 0.8192  |
| $T_w$ | 0.9065   | 0.8204  |
| $T_{uf}$ | 0.8771 | 0.8060  |
| $T_{lf}$ | 0.8985 | 0.8170  |

As it was mentioned previously, the model was validated using 30% of the data (i.e. 157 readings) as testing sample for the purpose of models validation. This step contains feeding models with the testing environmental thermal loads as input and predicting the model output and comparing them with experimental one. The figure 4, A-D compares the predicted readings to the experimental. The prediction formulas shows that R is equal or more than 0.5 for the models predicting $T_m$, $T_w$, $T_{uf}$ and $T_{lf}$. This implies the accuracy of the prediction done in this work. Table 2 presents the mean absolute error of the prediction formula for both training and testing samples. It can be seen that the average temperature prediction differences are less than 1.5 °C for the training samples and ranges from 3.2 to 3.8 °C. These MAE are fully accepted when compared to the range of beam temperatures at different parts.

### Table 2. The mean absolute error (MAE) of training and testing sample prediction

| Model | Training (°C) | Testing (°C) |
|-------|---------------|--------------|
| $T_m$ | 1.2           | 3.3          |
| $T_w$ | 1.2           | 3.2          |
| $T_{uf}$ | 1.4  | 3.9          |
| $T_{lf}$ | 1.1  | 3.3          |
Figure 4. Probability distribution of the model residuals, A) $T_m$ model B) $T_w$ model C) $T_{uf}$ model and D) $T_{lf}$ model

5. Conclusion

This study presents a study for prediction of beam temperatures based on the environmental thermal loads using linear multivariate regression modelling. The modeling targets the beam mean temperature $T_m$, beam web mean temperature, upper flange temperature and lower flange temperature. Beam temperatures were recorded experimentally. From this work, some conclusions can be shown below:

- Beam temperature can be accurately predicted based on environmental thermal loads. These prediction were furtherly validated and the validation shows over 0.9 of correlation coefficients.
- The prediction shows that the absolute temperature error was around 3.5 °C which are successfully accepted when compared to the temperature range in summer.
- The predictions target different parts of the beam section and all these predictions were have good performance.
Although the prediction formulas performs accurately in this study, further research can be conducted for investigating the effect of data preprocessing on improving the model performance.

6. References

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