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Thermal gradient effects on steel I-girders in bridges: A review

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Abstract

Steel I-girders in bridges experience thermal gradients induced by environmental factors, which generate non-uniform stresses, resulting in deformation, fatigue, and dynamic impacts, causing reduced service life. This review consolidates the numerical, experimental, and field-measured data-based studies to examine the effects of thermal gradient stresses on steel I-girder in bridges, emphasizing gaps in current design approaches, such as their limited focus on transverse thermal effects and nonlinear temperature gradients. Key outcomes highlight that both vertical and transverse thermal effects often exceed the values assumed in bridge design codes, with transverse stresses contributing significantly to the overall stress of curved bridges. Finite element analysis methods realistically simulate these thermal effects. Advanced sensors in field measurements, such as Fiber Bragg Grating systems, highlight the importance of location-specific thermal profiles. This review advocates adaptive design strategies, including advanced thermal models, optimized girder geometries, and flexible bearing placement to minimize and deal with thermal stresses.

Keywords: I-girder; Steel bridge; Thermal gradient; Thermal stresses

1 Introduction

Steel I-girder is one of the primary components in modern structures because of its load-bearing capability, economy, and ability to support long spans. Environmental factors and non-uniform heating and cooling of the bridge elements lead to thermal gradients, thus creating non-uniform thermal stresses. Such stresses affect structural performance as they result in deformation, leading to fatigue failures, frequent repairs, and reduced life expectancy of structures (Mosavi et al., 2012). Moreover, these temperature-induced variations can significantly affect dynamic properties, such as modal frequencies, complicating structural health monitoring systems (Li et al., 2023).

Design codes, such as those developed by AASHTO, provide critical guidance on controlling temperature-related effects on structural elements. The design codes are established to uphold the structural integrity and safety of transport systems by defining allowable temperature gradients that must remain within predetermined limits. However, studies have pointed out that thermal conditions often exceed the recommended limits. This shift requires improved means of analysis and supervising tactics to appraise and suitably deal with the consequences of thermal fluctuation on infrastructure (Rojas, 2014).

This review combines the past studies on the effect of temperature gradients on steel I-girders, which are the essential parts of bridges. It assesses different methods, i.e., experimental tests on small-scale samples in controlled environments, numerical simulations that mimic real-world scenarios, and the analysis of existing installations. This work aims to uncover our knowledge gaps on the thermal effects on steel I-girders and simultaneously compare and collect diverging information from multidisciplinary sources. Besides, it will provide suggestions on improving the design methods and management strategies, ensuring that these structures are well-preserved and function effectively under changing climate conditions.

2 Fundamentals of thermal gradients in bridges - temperature distribution

The temperature distribution on bridges is typically nonlinear and depends on various factors, including the materials used, the bridge's location and orientation, and the shading from nearby structures. Several studies have performed experiments, including temperature variation measurements in bridge girders. According to (Borah et al., 2021), the maximum temperatures measured at various points on the National Physical Laboratory footbridge in Exeter, UK, varied between 26.8°C and 35.4°. Similarly, (Zhou & Sun, 2019) observed maximum and minimum temperature variations in the vertical and transverse directions in steel girders of the Shanghai Yangtze River Bridge throughout different seasons (summer and winter). They did not find any significant transverse thermal gradient in steel girders. However, they observed a large vertical temperature gradient exceeding 20°C between the top and bottom plates during hot summer days.
In a study by (Lawson et al., 2019), thermal profiles throughout the depth of the hypothetical concrete and composite beams were modeled using weather data from Nevada, USA. The top surfaces of the concrete superstructure elements experienced the highest daily temperature fluctuations. Meanwhile, the bottom and internal layers have decreased fluctuations. Regarding the composite superstructure elements, the temperature fluctuation in concrete was confined to itself, while the steel layer maintained practically a uniform temperature. It has been commonly observed that temperature differences along the depth of both superstructures frequently exceeded 30°C, with a maximum of over 40°C in the concrete superstructure and 36°C in the composite superstructure. These results underlined significant temperature gradients, which are usually developed in bridges, but especially along the depth of these, due to the ambient conditions and solar radiation.

3 Effects of thermal gradients on I-girders

The vertical thermal gradient of an I-girder (W40x235) was studied by (Abid & Al-Gasham, 2020) in an exposed environment. The resulting thermal effects found to be influential exist in the girder cross-section, which is subjected to environmental heating and cooling throughout the day and varying seasons.
Therefore, (Abid et al., 2021) analyzed that during the bridge construction and in the service stage, thermal gradients can cause additional stresses in the I-girders. These extra stresses may vary based on the geometry, temperature variations, and the intensity of solar radiation on different parts of the girders. According to (Wang et al., 2023), these temperature gradients may induce significant thermal stresses and deformations comparable to the condition when the girder is subjected to static and dynamic loads. The possible damage to the whole bridge structure underlines the urgency of taking care of temperature gradients in the design of a bridge. Thermal stresses play an important role in designing steel-concrete composite bridges because they induce significant stress and deformation.
Similarly, (Nassar & Amleh, 2023) found that traditional models, such as those in existing national standards, usually cannot capture the complex behavior of thermal gradients and their effects on composite girders.

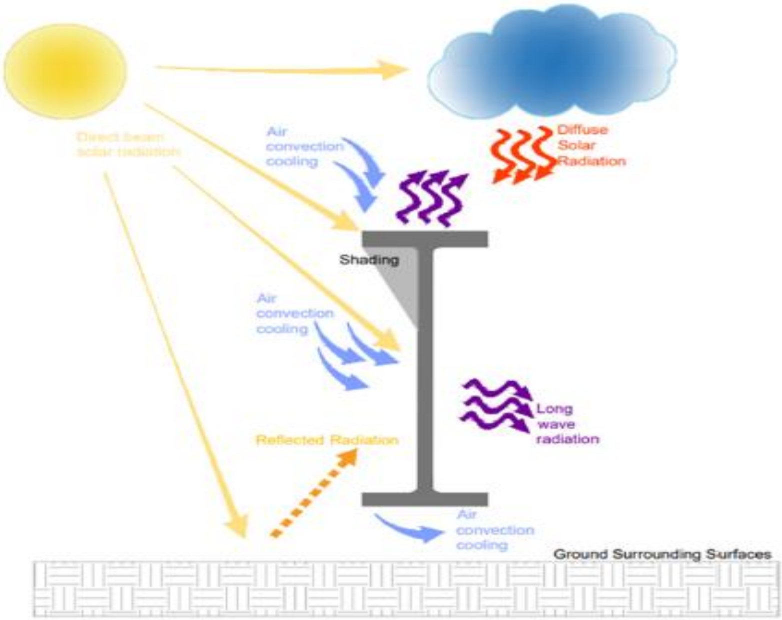

Fig. 1. The thermal boundary conditions (Nassar & Amleh, 2023)

In another study, (Wang et al., 2023) proposed two new vertical thermal load models denoted VTLM I and VTLM II. VTLM I simplify positive and negative temperature gradients by expressing them as piecewise linear functions; VTLM II decomposes the vertical nonlinear temperature gradient into three components: equivalent uniform temperature (T_T), equivalent linear temperature (T_L), and equivalent nonlinear temperature (T_{NL}). Such a decomposition allows a deeper understanding of thermal self-stress and secondary thermal stress.

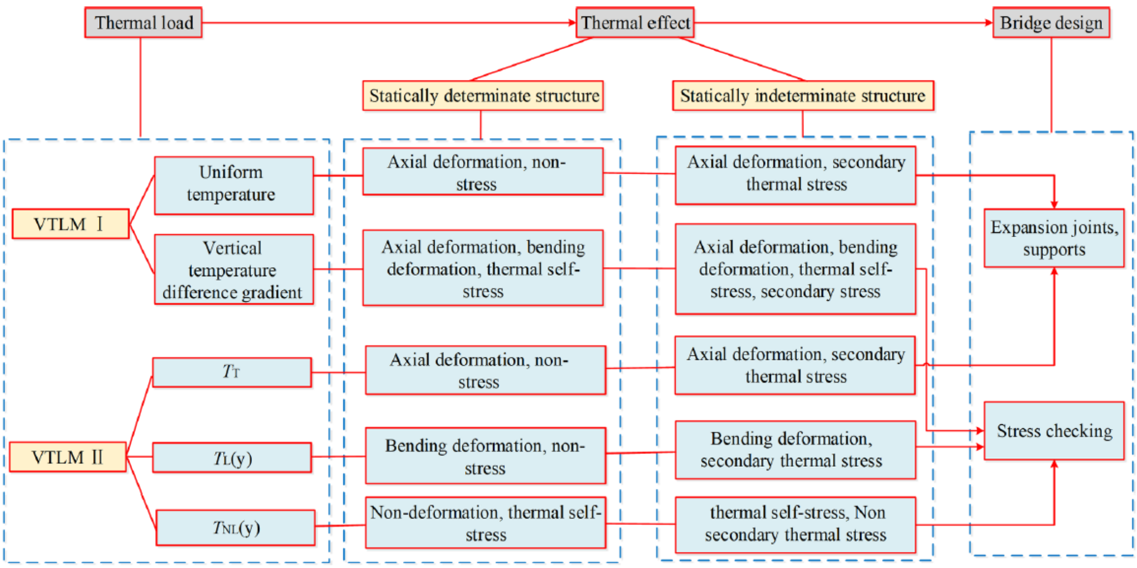

Fig. 2. Relationship between the thermal effects and thermal loads (Wang et al., 2023)

Similarly, (Lei et al., 2019) studied the thermal effects on the stability of bridges. The investigation focused on a curved bridge by analyzing the thermal gradient stresses in longitudinal and transverse directions. Its findings also showed that transverse stresses were also important and needed to be incorporated during the design process. However, most design guidelines only consider vertical thermal differentials during the design process. This study demonstrates that transverse temperature differences lead to considerable thermal stresses and displacements in the curved bridge, in contrast to the effects of vertical temperature variations. Over 60% of curved bridge loads and displacements under vertical temperature changes are caused by transverse temperature variations.

4 Numerical methods for analyzing thermal gradient effects

Research into numerical methods to analyze thermal effects on structural components has continued since the 20th century. In 1975, Kehlbeck proposed a theoretical solution assuming the existence of one-dimensional heat flow. This was a significant advance, which Emerson later developed into the finite difference model. Hunt and Cook further refined this model. This led to the finite element analysis (FEA) we use today (Tong et al., n.d.).

The capability of FEA in analyzing thermal gradients has been assessed in several studies, (Meyghani et al., 2017) suggested that FEA has been quite beneficial in analyzing thermal gradients through heat transfer, material flow, and deformation simulation. The data obtained used three principal methods, including the Lagrangian method (creates a mesh to be deformed by the material which makes it ideal for global heat stress analysis in which the deformation of the mesh is minimal), Eulerian method (uses a fixed grid and effectively captures the material flow. However, it is less able to handle local thermal gradients), and Arbitrary Lagrangian-Eulerian (ALE) method (combines the power of Lagrangian and Eulerian methods, which facilitates accurate investigation of boundaries and deformations. Especially in areas such as heat-affected zones (HAZ)).

The ALE method better captures effects with large deformation and temperature gradients across the cross-section, while the Lagrangian method is more suitable at a steady state. The ALE method can provide the best insights for temperature gradient analysis in the context of steel I-girders in bridges. Collectively, these approaches address complex thermal effects and greatly enhance the precision of simulation and its applicability in engineering analysis. (Abid et al., 2018) also assessed the ability of FEA to accurately predict the temperature and its variations in the case of a concrete-encased I-Girder.

5 Experimental studies and field measurements

The thermal load in a bridge is influenced by air temperature, solar radiation, humidity, wind, material type, and so on, making it difficult to model by theoretical or numerical approaches. Therefore, the Fiber Bragg Grating (FBG) temperature sensor is frequently used for temperature testing due to its exceptional qualities of high sensitivity, small size, insensitivity to electric or magnetic inference, localized strain measurement capabilities, and multiplexing capability (Ren et al., 2004; Sun et al., 2016).

Additionally, sensors that measure other physical parameters, such as strain, displacement, and wireless acceleration sensors, usually have a temperature-detecting component (Guan et al., 2000; Kim et al., 2007; Yu et al., 2000). In general, there are four steps involved in processing field measurement data: data preparation, trend analysis, statistical analysis, and extreme value analysis (EVA) (Benstock & Cegla, 2017).

The temperatures of the steel girders, the concrete deck, the tower legs, the asphalt pavement, and the atmosphere were all examined by (Ni et al., 2007) using continuous measurement data for a year. The highest temperatures were found in asphalt, while the lowest in the atmosphere. Nearly at the same hour, the temperatures recorded at various points on the same cross-section reach their maximums. The extreme effective temperatures of the bridge deck with a specific return period were estimated using the EVA. For a return duration of 120 years, the expected maximum and minimum effective temperatures are 36.9°C and -3.6°C, respectively, which are in good agreement with the design values.

In another study by (Ding et al., 2012), an experiment was performed at a sampling frequency of 1 Hz, and the temperatures of the 1490-meter-long Runyang Suspension Bridge (RSB) have been tracked since 2005. A flat steel box girder primarily supported the bridge. Four cross-sections and eight embedded temperature sensors were measured in one piece. (Ding et al., 2012) examined sample data of 90 days that were uniformly distributed among four seasons in a single year. The findings showed a strong correlation between the cross-sectional temperatures and the season.

6 Results and Discussions

*6.1 **Material and geometric influences on the thermal behavior of I-girders***

The thermal behavior of I-girders is influenced by the shapes and materials used. This interaction affects how well they perform in different environmental conditions. Because of its high thermal conductivity and low thermal inertia, steel, the primary material used for I-girders, changes temperature rapidly and nonuniformly in its sections when subjected to wind, sunlight, and changes in air temperature. Thermally generated strains and distortions may result from the large vertical and horizontal temperature gradients created by this. For example, limited thermal expansion increases the potential for thermal strains to spread into substructure elements such as piers and bearing assemblies, particularly in bridges with fixed and guided bearings (Beckett et al., n.d.; Helwig et al., n.d.).
Geometric parameters such as girder depth, flange width, and spacing are critical in determining the thermal response. For example, deep girders tend to have higher vertical temperature gradients because of the increased exposure to unequal heating. At the same time, a larger width of flanges can help distribute thermal stress more uniformly (Nassar & Amleh, 2023). Special thermal behaviors characterize composite girder systems of steel and concrete. The differential expansion between the materials creates additional stresses that must be precisely modeled to capture such interactions (Chang & Im, 2000). Figures 3 and 4 show how different geometries of I-girders and vertical thermal gradients lead to varying thermal stress based on the geometry.

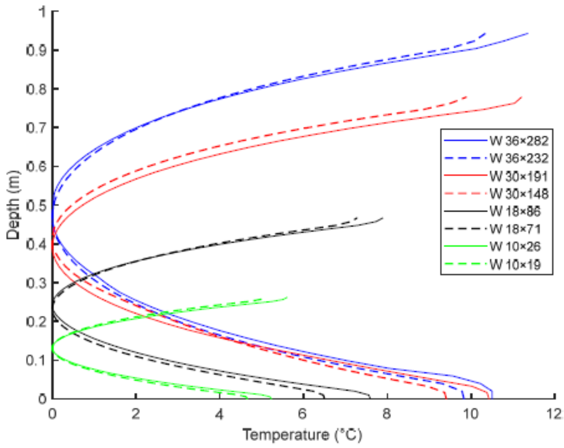

Fig. 3. Positive vertical thermal gradient (Nassar & Amleh, 2023)

The finite element analysis was conducted by (Abid et al., 2021) using COMSOL Multiphysics to evaluate the effects of geometrical parameters on thermal responses, including temperature gradients and induced stresses. Four I-girders, two of each, W12 and W24 standard steel beams, were analyzed under changing solar conditions throughout the day. The results show that the flange's thickness and width are mainly responsible for the extent of temperature variations and induced stresses, with thinner flanges revealing faster temperature changes due to their reduced thermal mass. For example, the W12 × 58 section, with a W_f/t_f^2 (flange width-to-thickness) ratio of 0.96, recorded the highest noon top-surface temperature, while W24 × 84, with a ratio of 0.60, showed the lowest temperature. Web thickness and depth also influenced thermal gradients, as shallower beams with thinner webs exhibited higher mid-depth temperatures due to faster heat conduction. Based on these findings, we can highlight the significance of considering the geometrical parameters and ratios, such as W_f/t_f^2 and $2W_f/Ht_f$ (flange width to the product of flange thickness and half the section's depth ratio), in predicting thermal stresses, particularly during peak solar radiation hours. The results are vital for optimizing steel beam designs to reduce thermal stress risks and enhance structural durability in response to environmental exposure.

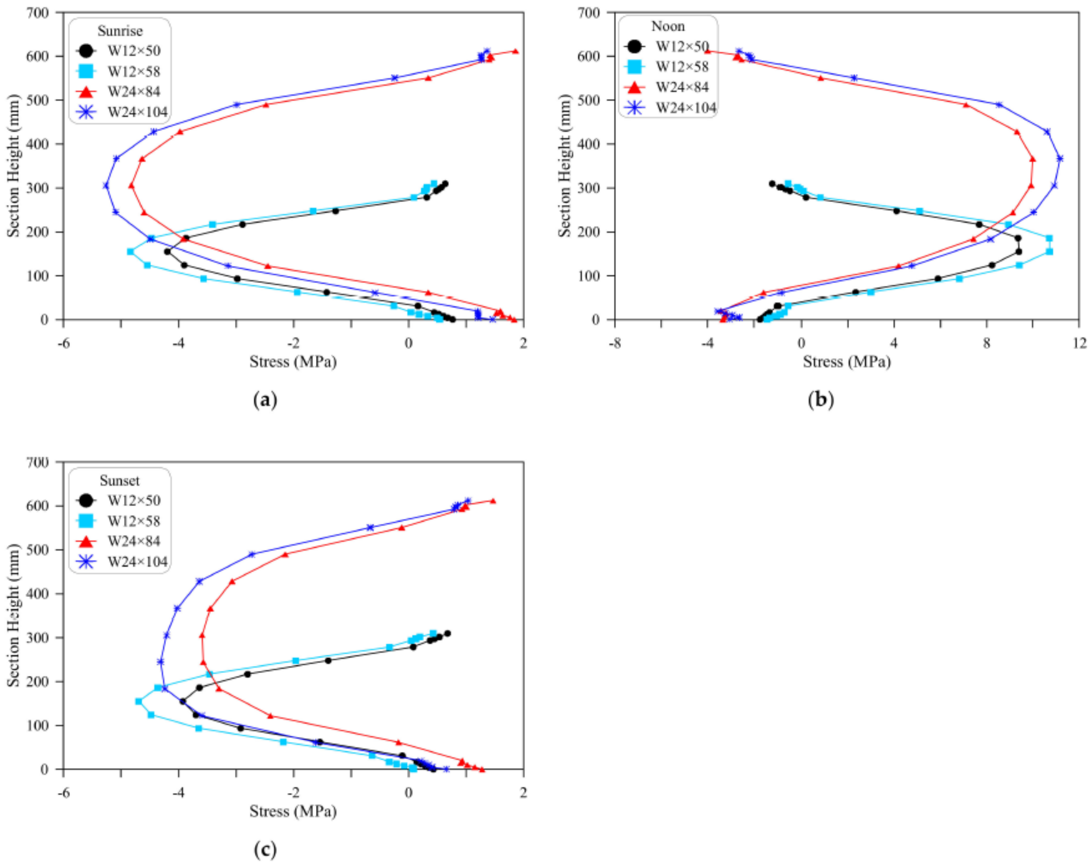

Fig. 4. Thermal stresses of the four sections: (a) At sunrise, (b) At noon and (c) At sunset (Abid et al., 2021)

Studies and analysis have concluded that there is a need for adaptive design guidelines that can account for the changing conditions. For example, placing the fixed bearings at points without movement allows other supports to be flexible and reduces stress concentrations. Similarly, analysis of high solar radiation and extreme temperature variations with seasons will help predict the local thermal gradients and mitigate stresses (Beckett et al., n.d.). The role in developing and implementing these strategies is crucial. These findings show that the material's properties, geometric optimization, and environmental considerations are essential to designing safe and durable I-girder structures under thermal loads.

7 Conclusion

This review emphasizes the impact of thermal gradients on steel I-girders. It discusses the temperature gradient's role in inducing non-uniform stresses and its dynamic impacts. With experimental investigations and field studies, it is demonstrated that temperature-induced variations often exceed the assumptions in design processes, which necessitates more refined approaches to account for this complex coaction of environmental variables, geometric configurations of the bridge and its components, and material properties. Modern numerical methods, including the finite element method (FEA), have shown a significant ability to accurately predict the resulting stresses using a temperature distribution model, particularly for composite and curved girders under extreme thermal conditions.

Studies have shown that geometric parameters, including flange thickness, width, and web depth, deeply influence the thermal responses in I-girders when exposed to the environment on site. The thinner the flanges, the more stress will be concentrated due to their reduced thermal mass during peak solar exposure. The assessment of stress distribution with varying geometrical parameters underlines the importance of parameters such as Wf/tf^2 and Wf/Htf ratios in optimizing the girder design for thermal resilience.

The field data measurements also reveal the significance of transverse and vertical temperature gradients. Particularly in curved and composite bridges, transverse thermal effects contribute over 60% of the stresses compared to vertical gradients. However, the current design standards only focus on the vertical gradients while often neglecting the equally critical transverse effects.

To improve the structural performance of steel I-girder, design approaches must incorporate location-specific thermal profiles and adopt advanced thermal models that can decompose nonlinear thermal gradients into manageable components that are easy to deal with. Adopting adaptive bearing placement strategies such as positioning fixed bearings to minimize thermal restraint and optimizing girder geometries can mitigate stress concentrations and improve thermal behavior.

Future efforts would be required to develop an integrated and flexible design framework, including advanced numerical models, performance-enhanced field monitoring systems, and substantial geometric optimizations. These efforts are to address the thermal problems experienced by modern steel I-girder bridges and form the basis for further research into their effectiveness, durability, and performance against future climatic and operational conditions.

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