Type of the Paper (Proceeding Paper, Abstract, Editorial, etc.)

Preliminary Investigation on the Evaluation of Bolted Joint Conditions Using Infrared Thermography.

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† Presented at the "Advanced Infrared Technology and Application (AITA)" in Kobe, Japan, on 15-19 September 2025

Abstract

Bolt connections are a critical component in steel structure design. After a period of operation, bolts in steel structures may experience loosening due to prolonged external forces or fatigue, posing a potential threat to overall structural safety. Currently, the practical method for detecting loose bolts in steel structures typically involves contact-based assessment, specifically using a torque wrench for testing. However, given the numerous bolts in a connection design, this contact-based evaluation method is inefficient for large-scale bridge bolt connection areas and is extremely time-consuming. To address this issue, this preliminary study explores the use of infrared thermography to assess bolt temperature changes during connection behavior and further evaluate bolt tightness. The analysis method integrates advanced image processing and time series analysis techniques to identify abnormal temperature distribution and temperature gradients in the connection area, establishing quantifiable indicators for bolt temperature status.

Keywords: Infrared Thermography, Bolts, Steel Structures, Image Processing

1. Research Motivation

Many bridges in Taiwan predominantly utilize steel structure design, with connections between steel components primarily achieved through welding or bolted joints. However, after construction, these structures face challenges such as aging, deterioration, and extreme weather. Effective management and maintenance are crucial to ensure that these facilities perform as expected throughout their operational lifespan. Over time, bolts can gradually deteriorate due to prolonged external forces and fatigue effects, posing a potential hazard to overall structural safety. Traditional contact-based inspection methods, unfortunately, are time-consuming and labor-intensive, making it difficult to efficiently monitor large-scale bridge structures. This study utilizes infrared thermography to detect temperature changes in bolts. By combining image processing with temperature differences in curve graphs, it aims to differentiate the significant thermal variations observed under different torque conditions, specifically between standard torque values and insufficient pre-tightening forces.

Received:

Revised:

Accepted:

Published:

Citation: Lastname, F.; Lastname, F.; Lastname, F. Title. Journal Not Specified 2025, 1, 0. https://doi.org/

2. Infrared Thermography Experimental Method

Steel structural materials are a common choice for bridges and large-scale engineering projects due to their superior mechanical properties and ductility. Connections between components are primarily established through welding and bolted joints. This research aims to delve into the behavior of bolted joints, utilizing infrared thermography to assess the thermal response characteristics of M12 high-strength bolts under varying pre-tightening torque conditions. By applying mechanical vibration to bolt-steel structure specimens, we precisely observe the differences in heat distribution generated by microscopic friction at their contact surfaces. This allows us to identify thermal signatures indicating whether the pre-tightening force is at the standard value or insufficient. The overall experimental design incorporates torque values from a torque wrench, active vibratory thermal energy, and continuous thermal image acquisition, combined with advanced data processing for temperature visualization and analysis. The thermal image data is captured using a Thermo Gear-G120 infrared thermal imager, which boasts a 320x240 pixel resolution.

3. Experimental Methods

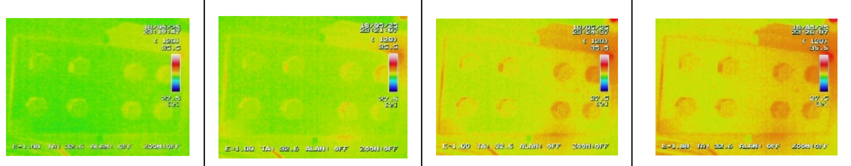
The specimen is an H-beam steel structure measuring 70 × 30 × 15 cm. It is equipped with 8 M12 bolts, each subjected to varying torque values ranging from 1.3 N·m to 135.6 N·m, simulating both insufficient pre-tightening and standard torque conditions. To replicate the dynamic loads experienced by structures in the field, a HY-15DC small DC electric motor (3000 RPM) is used for vibration during the experiment. This vibration device is designed to induce minute friction and localized heat at the bolt contact surfaces, allowing for the identification of temperature differences through thermal imaging.

H-beam	Bolt Dimensions	Number of Bolts	Torque Value	Time	Images
H1	M12	8	1.3	10 Min	30
	M12	8	13.56	10 Min	30
	M12	8	27.12	10 Min	30
	M12	8	40.68	10 Min	30
	M12	8	54.24	10 Min	30
	M12	8	67.8	10 Min	30
	M12	8	81.36	10 Min	30
	M12	8	94.92	10 Min	30
	M12	8	108.48	10 Min	30
	M12	8	122.04	10 Min	30
	M12	8	135.6	10 Min	30

Table 1: H-beam, Bolt, and Time Detail Drawing with Dimensions.

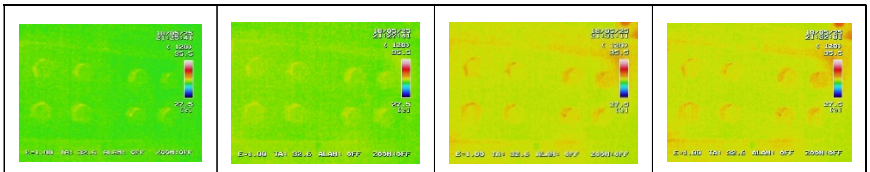
4. Experimental Analysis

The Thermo Gear-G120 infrared thermal imager, with its 320x240 pixel resolution, effectively captures infrared energy radiated from object surfaces due to minute temperature changes (within the 8 to 14 μm wavelength range), converting it into real-time visual thermal images. Each pixel corresponds to a temperature value with physical significance. When a component, such as a bolt, experiences insufficient pre-tightening, friction, or external vibration, its localized temperature distribution will show abnormal changes. As the torque wrench applies different pre-tightening forces to the bolts, the frictional heat generated between the bolts and the H-beam during vibration also varies, leading to differing magnitudes of surface temperature increase. As shown in the figure, Figure (A) displays the initial thermal distribution (1st image); by Figure (B) (5th image), a slight localized temperature rise is observable. By Figure (C) (15th image) and Figure (D) (26th image), the effects of vibration and friction become significant, with a more pronounced temperature increase in the bolt contact areas and a tendency for the hot zones to become concentrated. These results demonstrate a positive correlation between bolt torque magnitude and thermal response behavior, which can be observed and interpreted over time using infrared thermal imaging.



(A) (B) (C) (D)

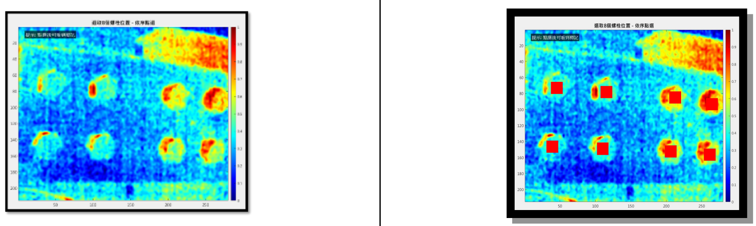
Figure 1 (When the torque value is: 1.3 N·m).



(A) (B) (C) (D)

Figure 2 (When the torque value is: 122 N·m)

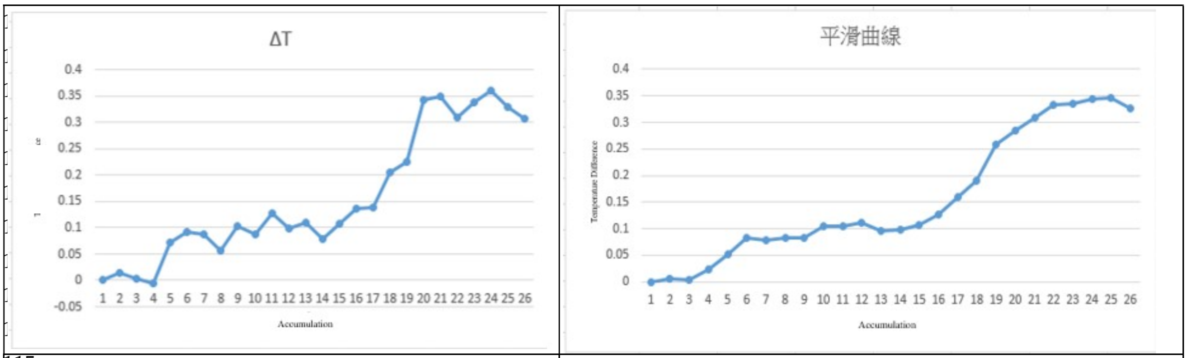
All thermal images were exported in Excel format via InfReC Analyzer NS9500 analysis software, then subjected to further processing and analysis using custom MATLAB code, as depicted in Figure (A). To enhance the accuracy of temperature information and mitigate external noise interference, this study selected a 5x5 pixel area, indicated by the red box in Figure (B), as the representative temperature region for each bolt's location. This allowed for the calculation of regional average temperature values, thereby establishing data stability for the thermal characteristics.



(A) (B)

Figure 3: Thermal Images Before and After Processing

The temperature change is calculated by determining the regional average temperature value. The temperature change ΔT for each time point is calculated as shown in Figure (A), where T(N) represents the temperature at the Nth image, and T(1) is the baseline temperature at the initial time point. To minimize real-time noise and spike interference, all ΔT curves are smoothed using a three-point moving average, as depicted in Figure (B).



(A) (B)

Figure 4: Cumulative Temperature Difference Curves

4. **Summary**

This research utilized infrared thermography to detect and analyze the heat energy and its distribution generated by microscopic friction between the steel plate and bolt contact surfaces on an H-beam steel structure when subjected to external vibration. Using the acquired thermal image data, the study transformed the average temperature changes in the bolt regions into continuous time-series line graphs via the MATLAB platform. This process incorporated smoothing techniques to effectively enhance the accuracy of trend identification.

Experimental results clearly show that the pre-tightening torque status of a bolt has a decisive influence on its thermal response pattern. When a bolt is insufficiently pre-tensioned, the reduced stability of its contact surfaces leads to more significant frictional effects. This results in a highly variable temperature increase trend observed in thermal images, and the temperature difference curves for individual bolts clearly exhibit a pronounced dispersion phenomenon. This suggests uneven heat accumulation or potential issues with poor contact.

In contrast, when the bolt torque value reaches or exceeds the standard specification range, the contact interface between the bolt and the steel structure becomes much tighter, leading to a significant reduction in frictional effects and, consequently, stable thermal behavior. In this state, the temperature change trends of individual bolts exhibit high consistency, and their temperature difference curves show stable and highly convergent characteristics. These observations clearly demonstrate that infrared thermography can effectively reflect the actual state of bolt connections, and through the specific curve graph patterns it presents, the current pre-tightening force status of bolts can be preliminarily identified.

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