BSC CIVIL ENGINEERING

THESIS REPORT

INVESTIGATIONS INTO TEMPERATURE DISTRIBUTIONS ON BRIDGE VIBRATION PARAMETERS: THE UT CAMPUS BRIDGE

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Preface

The research proposed in this report is a part of the third year of the bachelor program of Civil Engineering at the University of Twente. This research conclude my three-year long journey to completing my studies. The project has been conducted under the supervision of Dr. Rolands Kromanis. As a part of the research about structural health monitoring (SHM) at the UT, led by Dr. Rolands Kromanis. The research focus on monitoring bridge health through the use of sensors such as temperature, load cells, accelerometers and vision- based systems.

I would like to send special thanks to Dr. Rolands Kromanis for offering me such excellent guidance and great support throughout the unexpected struggles that I have experienced during my work, investing his valuable time to supervise my work and provide me with feedback, challenging me, guiding me and pushing my limits. I would also like to thank my co-supervisor Dr. Rosalie Arendt, for investing in her valuable time in order to assess my report.

Finally, great thanks to my parent, especially my father, for supporting and investing in me throughout the whole journey.

Seif abdelbary, 2024.

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Abstract

Structural health monitoring (SHM) has a critical role ensuring safety and integrity of structures through analyzing data gathered from sensors implemented on the structures. Through advanced SHM methodologies, the proposed research investigates the effect of temperature distribution on the UT Campus footbridge structure parameters. The influence of the temperature variations on structural dynamics, is rather underestimated. Temperature variation can obscure mode shapes and natural frequencies of structures affecting the accuracy of dynamic response assessment. Information about the UT Campus footbridge such as the geographical location and data collection points are gathered. Temperature data are collected from the sensors implemented on the bridge. With consideration of environmental conditions, such as solar exposure and seasonal temperature changes, the temperature data of 11 scenarios are analysed and visualized. Assessing the bridge response to user induced vibrations, particularly cyclists, an acceleration analysis was conducted. Similarly, to the temperature analysis, acceleration data are derived from contact sensors at specified locations on the bridge. Using Fast Fourier Transformation (FFT) , the raw acceleration data collected are transformed from time domain to frequency domain. Welch's method is then applied in order to assess the dominant frequency peaks by estimating the power spectral densities. The dominant peaks visualized in a PSD plot refer to the natural frequency of the bridge. The research was able to identify the temperature distributions as the sensors on T1 and T5 located on girder C of the footbridge, recorded higher temperature variations throughout the scenarios compared to the temperature sensors T2 and T4 located on girder A. Six crossings corresponding to 6 temperature scenarios were analyzed showing natural frequencies ranging from 3.26 – 2.82 Hz. Across the 6 crossing the value of 2.82 Hz was identified to be out of bounds therefore the natural frequency of bridge in response to cyclists crossing were deducted to be in range of 3.2 – 3.26 Hz. The sixth crossing lies in the coldest scenario among other crossings. Therefore, this temperature drop followed by the frequency shift can give an identification of possible effect of temperature change on bridge dynamic parameters. Further, the research discusses the possible limitations of the study as well as further research to be conducted.

Keywords: Structural health monitoring . Dynamic response . Temperature variations . Vibrations . Natural frequency . Limitations

1 Introduction

Footbridges play a crucial role in the evolving landscape of urban infrastructure, with history predating road bridges. A deepening understanding of that history is particularly relevant to current circumstances, as the characteristics of footbridges underwent remarkable transformations, which became noticeable towards the end of the eighteenth century, marked by the enlightenment of ideas, industrialization, and rapid economic growth. These circumstances combined to propel social and technological transformation, thereby traffic and mobility. Moreover, advanced transportation in the early nineteenth century (first railroads, then canal ways and turnpikes) played a pivotal role in reconfiguring the baseline of the bridge construction; new standards were posed. While the overall evolution of footbridges took place as a separate developmental path, it was indirectly influenced by the divergence in the technological landscape and was simultaneously driven by its own multi-dimensional challenges and innovations in functionality, aesthetics, and structural integrity (Baus & Schlaich, 2008). More recently, with the increase of expenditures on bridge maintenance, integration of sensing technology has become essential for its potential to reduce lifecycle costs within bridge management (Kromanis & Kripakaran, 2014). The concept of smart technology, this futuristic approach, establishes a significant challenge for bridge engineers in organizing and interpreting the collected data.

Structures, including bridges, buildings, dams, and other civil infrastructure, are subject to diverse external loads throughout their lifespan. The initial design process typically considers live and dead loads to ensure the safe construction of structures for use by civilians. However, when structures are exposed to these loads over an extended period, issues such as cracking and degradation can occur. In the case of footbridges, induced loads by pedestrians tend to translate slowly, however resulting in harmonic excitation causing moderately high displacements and deformations (Garcia et al., 2019).

Footbridges play a crucial role in urban infrastructure and development by providing safe paths for cyclists and pedestrians. As efficient and sustainable urban mobility and commuting grow, in line with the goals of the Paris Agreement, investigating and understanding the dynamic behavior of footbridges becomes essential. Therefore, it is important to consider Structural Health Monitoring (SHM) to anticipate potential damage and promptly address issues, enhancing the overall understanding of bridge response.

SHM provides data for structural assessment and contributing to the more efficient operational safety of the structure. Advanced methodologies in SHM involve the investigation and interpretation of dynamic response through the application of statistical tools and machine learning algorithms (Ceravolo et al., 2021). This process involves collecting data from sensors applied to the structure, followed by data management, preprocessing, and visualization and then finally, using these specific data for analysis and assessment.

One factor that significantly affects a bridge’s performance yet is often underestimated is temperature. Temperature fluctuations influence the structural integrity of a bridge, which obscures the interpretation of its natural frequencies and mode shapes due to their nondynamic nature. In response to these temperature variations, dynamic parameters such as acceleration and strain may present nuanced changes in their vibrations, which make it imperative to define and assess the dynamic response accurately.

The proposed research seeks to investigate and prove the effect of temperature changes on a footbridge, specifically the UT Campus footbridge, through data analysis and visualization techniques. Moreover, the “funnel-method” will guide this investigation, for which it begins with a broad spectrum of analysis before narrowing down to the scope of the research. This paper will firstly discuss the problem statement, objectives, questions, and scope of the research. Secondly, a literature review, including relevant research papers that outline theories and key concepts, methodological approaches for the research as well as identifying knowledge gaps. Followed by the methodology section, discussing an overview of the project aspects, and showing how the research was conducted. Then the results will be presented with a case study showing the details of the UT Campus footbridge. Furthermore, the results will be validated and discussed to ensure relevance and integrity. In the end the paper will be concluded along with further research.

1.1 Problem statement

The main focus of this research is to investigate the temperature distributions on bridge vibration parameter, and to understand how that affects the dynamics assessment of the footbridge. In addition to the literature that provides valuable information about temperature and SHM, however with a noticeable gap in the interactions between the changing temperature and the footbridge’s response mainly distributed temperature. The procedure will take place by assessing thermoprofile data and analyzing acceleration response through modelling an simulation, in order to visualize the vibration fluctuations in comparison to different temperature scenarios. Therefore, This can be concluded in correlating temperature and acceleration analysis to assess the effect on the bridge dynamic response.

1.2 Research aim & objectives

The aim of this paper is to investigate the relationship between temperature variations and the dynamic response of the UT Campus footbridge. Through analyzing temperature and acceleration data, applying SHM methodologies.

The study aims to show an intercorrelation analysis between temperature changes and the bridge structural vibrations collected by acceleration sensors, and then visualizing it throughout modelling techniques. Therefore, seeking a comprehensive understanding of whether temperature fluctuations affect the structural dynamics of the footbridge.

The objectives of this study are:

- Review relevant literature outlining the theories and methodological approaches necessary to support the study.
- Development of methodology, applying SHM paradigm.
- select a variety of temperature distributions of the UT Campus footbridge.
- Analyze changes of bridge vibration parameters induced by distributed temperatures.
- Quantify and visualize the effect of temperature variations on the bridge structural dynamics.

1.4 Scope and limitations

The scope of thesis research is to analyze the intricate relationship between temperature fluctuations and their impact on the dynamic response of the UT Campus footbridge. This investigation focuses on how temperature fluctuations influence the vibration parameters of the footbridge, through detailed analysis of thermoprofile data and acceleration responses which are captured by sensing technologies. Moreover, SHM methodologies are applied to precise data sets, which are collected under a series of eleven scenarios, representing a range of temperature sensors readings showing variations at different locations on the bridge.

Furthermore, utilizing the data obtained from acceleration sensors is essential, serving as a foundation for the analysis aimed at visualizing the bridge’s vibrations in response to the chosen scenarios. Finally, correlating both temperature and acceleration analysis, in order to conclude a useful insight into how the distributed temperature can affect the dynamics of a structure. Therefore, contributing into the field of civil engineering, particularly structural health monitoring, supporting the development of predictive models for bridge behavior under varying temperatures.

On the other hand, as the research is specifically examining the UT Campus footbridge, therefore findings may not generally apply to all footbridges. In addition to the specific dataset used in the project, drawing boundaries for the investigation considering other conditions that are not involved in that research. Another limitation is the excessive volume of data that has to be analyzed, therefore affecting the depth of the study along with other long periods of missing temperature data that may have affected the accuracy of the results. It is critical to highlight the limitations of such a project while interpreting the outcomes.

2 Literature review

In order to develop a comprehensive understanding regarding the proposed study, it is important to explore other resources that will help with addressing the scope of the study as well as proposing different methodologies that can open a pathway of various acknowledgment.

The research is guided by the funnel method; therefore, this chapter first introduces the temperature effects on footbridges and structural dynamics, followed by finally SHM and data analysis.

2.1 Structural health monitoring

With recent advancements in sensor technology and data analytics, SHM has reached a high level of enhancement. This part of the literature review will be focusing on recent papers discussing the methodologies, applications, and innovations within SHM, along with the role of data analysis in that field.

SHM systems provide a method for evaluating and monitoring the health of different structures such as bridges, buildings, tunnels, and dams. It is identified as a non-destructive in-situ structural evaluation method, mainly involving several types of sensors implemented or attached to the desired structures to be monitored. SHM acts as a tool used to guarantee structural safety and integrity, through the detection of damage growth and the evaluation of the overall performance of the infrastructure (The Constructor, 2021).

Damage can be defined as” the changes to the material and/or geometric properties of the systems, including changes ti the boundary conditions and system connectivity, which adversely affect the system’s performance” (Farrar & Worden, 2006). The definition can be related indirectly to all SHM applications which include online monitoring. This requires the implementation of a sufficient sensor network system to efficiently assess the changes in the structure affecting its performance. The sensibility of such a system is identified by how good the interaction between the structure and the sensors is (Tibaduiza Burgos et al., 2020). Data collected from the installed sensors is to be analyzed for assessment of structural strength, safety, integrity, and performance (The Constructor., 2021).

The SHM paradigm consists of 4 main steps: (i) operational evaluation, (ii) data acquisition, (iii) feature extraction and information condensation, and (iv) statistical model development for feature discrimination. Firstly, the operation evaluation, which describes the motivation of a SHM system. Through identifying the damage and damage critical states, as well as safety and economic concerns. In addition to the acknowledgment of the operational and environmental conditions. Secondly, the data acquisition step, at which the sensors, locations, amount, and sampling frequency are decided. Those data are then smartly combined and polished. Moreover, the feature extraction step assesses the damage sensitivity acquired from the system responses observed. Linear modal qualities including, natural frequencies, mode shapes or the attributes derived from mode shapes such as flexibility coefficients are mostly used for damage identification. Furthermore, the last step requires the use of statistical model analysis in order to detect damages, their severity, and location (Sohn et al., 2004).

SHM methods can be characterized by two main approaches: model-based approaches and data-driven approaches. The first approach, model-based, includes the use of the theoretical information and data collected from the structure into building physical or mathematical models. Such models aid in the prediction of structural behaviors under various scenarios, considering various environmental and operational conditions. Finite element analysis (FEA) is regularly used in the model-based methods. Secondly, the data-driven approach mainly relies on the analysis of the data collected directly from the structures. The analysis is done by comparing the baseline data with the data collected in the current state of the structure (Farrar & Worden, 2006).

Additionally, the application of modal analysis (vibration analysis) assists for further damage detection, based on the changes occurring to the response of the structure due to that damage. Frequencies measured in Hertz demonstrate how often an action causing this vibration happens in a specific period usually measured in seconds (Reuven, 2020). Meanwhile, natural frequency describes the tendency at which a system oscillates without any damping force. With any shifts detected in the structure's natural frequencies, identifies the existence of damage or degradation in a structure (Salawu, 1997). Modes shapes are used to illustrate the initial displacements of a system that causes it to oscillate harmonically. Nonetheless, if a system contains various natural frequencies, then each one of these frequencies should correspond to a mode of vibration (Hashimoto et al., 2020).

With recent improvements in sensors, communication, and signal processing technologies, monitoring structural behavior with sufficient precision in order to assess damage levels and predict future structural health cycles became feasible (Huston, 2019). With day-to-day advancements, the next generation of SHM sensing technologies are cameras, mobile sensors, UAVs and smartphones (Sony et al., 2019). Regardless, data is collected using complicated sensor systems nowadays (Matarazzo et al., 2017).

2.2 Temperature effects on footbridge response and structural dynamics

Acknowledging the structural dynamics and the impact of temperature on footbridges responses is essential for ensuring resilience. Different studies have contributed to unravelling the complexities associated with temperature effects on footbridge behaviour as well as understanding the structural dynamics behind it.

The effects of dynamic forces and loads that cause relatively high vibrations on structural system, are described by structural dynamics. Dynamic forces are defined by the forces and loads that change in time. Those dynamic loads are caused by people, traffic, winds, or earthquakes that occur on the bridge. Loads induced by pedestrians or transversing vehicles affect the dynamic stresses within the structure, resulting in demanding vibrations, those vibrations are described as resonant vibrations (Mikolaj, 2021). Resonance vibrations occur when driving frequency reaches the natural frequency of the structure. Therefore, several occurrences of resonance vibrations can result in significant damage to the structures and hence reduce their lifespan. Resonance response was a reason for several lethal catastrophes such as the collapse of the Chester rail bridge in 1947 or the Tacoma highway bridge in 1940.

structural characterization process includes the design, testing and functioning of different products and solutions, for which structural dynamics and analysis plays a significant role. Such processes require the measurement of physical quantities such as accelerations, displacements, or strains. Those obtained measurements are essential in order to obtain qualitative and quantitative assessment of the structure. Moreover, modal parameter and mode shape associated with natural frequency are one of the key dynamic properties, giving comprehensive insights into the behavior and the condition of a structure (Mikolaj, 2021).

Frequency itself measured in Hertz (Hz) identifies the occurrence of a certain action in a specific period of time (in seconds). The frequency and the period are inversely proportional to each other. One full wave has a frequency that is an integral multiple of the natural frequency. Natural frequency, eigenfrequency, fundamental frequency are all synonyms of each other, defining the frequency at which a system or object vibrates after an initial disturbance. Or in other words, the oscillations of the system with no driving force applied (Avnon, 2022).

Degradation or damage of a structure causes the natural frequency of a structure to shift. Damage can be detected within a 5 percent change in the fundamental frequency. Nevertheless, only the change in the natural frequency does not factually translate to a damage in structure. Other conditions such as environmental conditions can affect the vibration response (Salawu, 1997).

Temperature as a load has the potential to cause ten times more stress than traffic load, therefore having an adverse effect on the structural integrity of the bridge and its components (Catbas, Susoy, & Frangopol, 2008). Bearings in bridge construction account for the contraction and expansion caused by temperature fluctuations, enabling translation and rotation, However, when these movements are restricted, structural components undergo excessive stresses, which affect the overall performance of the bridge (Goulet, Kripakaran, & Smith, 2015).

Moreover, temperature variation has the ability to change the stiffness of materials and thus the boundary conditions of a system. Ideally, natural frequencies decrease with increasing damage as its magnitude is proportionate to stiffness (Farrar, et al., 1996). In addition, daily temperature variation can cause the first mode's natural frequency to vary around 5% throughout a 24-hour period (Doebling & Farrar, 1997). While seasonal temperature fluctuations, tested for a 3-year period, can alter the natural frequencies of the bridge by around 10% per year (Askegaard & Mossing, 1998).

Bridge response is affected by environmental conditions such as temperature and humidity. Parameters are sensitive to these environmental factors, especially temperature (Mikolaj, 2021). Thus, causing difficulties in measuring and characterizing the bridge's response in the form of natural frequencies and mode shapes. In addition to changes in boundary or local damage, temperature can also have an impact as it shows significant variations seasonally in most of the regions around the world (Zolghadri et al. 2015).

Focusing on vibrations, it must be acknowledged that pedestrian footbridges are prone to both vertical and torsional vibrations, causing significant response, resulting in high vibration levels. In general, vibrations are not a critical reason for structural problems, nevertheless, due to exceeding acceleration values it can cause discomfort to the users (i.e., pedestrians). Vertical force is usually stronger than horizontal force, however, vibration problems for the structure can still be affected by both the vertical and the horizontal components (Marchenko,2020). The number of pedestrians crossing the footbridge influences the amplitude of natural frequency. Therefore, natural frequencies and vibration modes must be known in order to perform the dynamic analysis (Tadeu, et al., 2022). Generally, the range of walking frequencies for a pedestrian footbridge lies between 1.6 to 2.4 Hz (Gheitasi, Ozbulut, Usmani, Alipour, & Harris, 2016).

2.3 Conclusion & gaps in knowledge

The literature review has explored the structural health monitoring and the effects of the temperature on footbridge response and structural dynamics. Those key aspects are crucial to the proposed research.

In the essence of SHM, recent advancements in data analytics and sensor technology have highly contributed to enhancing the ability to monitor the health of different structures. Therefore, ensuring safety and integrity. SHM is assessed through series of steps, from operational evaluation to the development of statistical models. In addition to the employment of both model-based and data driven approaches. Moreover, the role played of the modal analysis in detecting structural damage through the observation of shifts in natural frequencies and mode shapes.

Furthermore, the literature review highlighted the importance of structural dynamics, definition, explanation and parameters. In addition to the detailed description of the definition and assessment of frequency and particularly natural frequency.

Moreover, the bridge response associated with temperature variations. And how it can affect the stiffness of materials and therefore the natural frequencies of the bridge. Furthermore, pedestrian footbridges that are susceptible to both torsional and vertical vibrations, due to pedestrian traffic and environmental conditions.

Furthermore, to assess the impact of temperature changes on footbridges comprehensively, it is important to realize the gaps found in the literature regarding this topic. Despite the research papers found on temperature changes in relevance to footbridge response, some gaps can be found. Firstly, both temperature effects and SHM are studied extensively individually, However, a solid integration between SHM and temperature effects can be missing. Most existing literature primarily indicate the short-term performance of footbridge under temperature variations. A gap in understanding the long-term temperature impact can be found. The literature shows the correlation between temperature and vibration properties, yet no in-depth investigation on the integrated effects on those vibration properties. Adding to that, existing approaches tend to ignore distributed temperature measurements (Kromanis & Kripakaran, 2014). Finally, a detailed understanding of dynamic response, which can help identify potential structural problems is needed. As most of the studies focus on outlining how strain and acceleration are affected by temperature.

3 Methodology

The methodology uses SHM and modal analysis, along with relevant approaches about temperature and structural data. This research is based mostly on visual analysis, which implies that data collected will be analyzed through various graphs and plots.

An overview of the project in order to study the temperature effects on the dynamic response is shown in figure 1. Firstly, the measurements are collected from the sensors installed on the desired structure to be monitored. Secondly the data are organized and classified into two categories to focus on, temperature as the load on the bridge and the vibration frequencies measured by the acceleration sensors. This step is followed by data interpretation where data is analyzed and then visualized showing temperature fluctuations through temperature mapping along with dynamic structural response by modal analysis. Finally, the results from the interpretation process are then correlated showing the effect of temperature on the structural performance of the bridge.

This part encompasses the four steps of the SHM paradigm. Understanding the case study, gathering information about the specific location of the structure. The amount, types and locations of the sensors implemented. Identifying the desired data to be used in the analysis. Applying visualization methods to conclude common trends or damages.

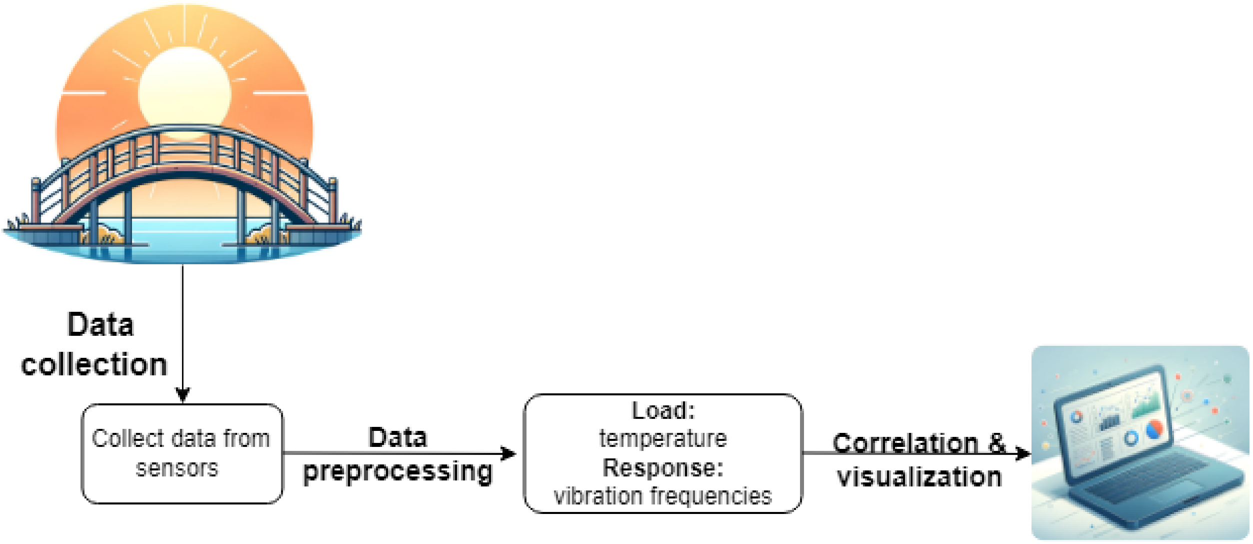


Figure 1: Fundamental methodology for contact sensors- SHM.

3.1 Temperature analysis

Temperature is considered as a critical environmental factor that can induce significant loads to a bridge, causing deformations or displacements (Behkambel et al, 2023). This research delves into a deeper understanding of the temperature distributions. Considering the structure location in reference to the sun path is essential in the assessment of temperature. The sun is the main source of temperature change; however, the exposure of sun is affected by the structure location. Apart from cloudy days, the high buildings and trees act as an isolation for direct sunlight on the structure. therefore, parts of the structure can experience more sun exposure than other parts. That cause the temperature to be distributed along the bridge. As a result, it is essential to monitor the distribution of different parts of the structure and not the structure as one system. The temperature data of the sensors placed at different known locations are collected. Specific scenarios are identified in different dates and times, related to environmental conditions. Scenarios are chosen in different seasons across the year. Ensuring the comprehensiveness of the study. After that, the data is analyzed and visualized through plots such as heat maps, line, and box plots. Identifying the temperature distribution across the desired scenario s. this process shown in figure 2, clarifies and summarizes the steps taken into temperature mapping and analysis.

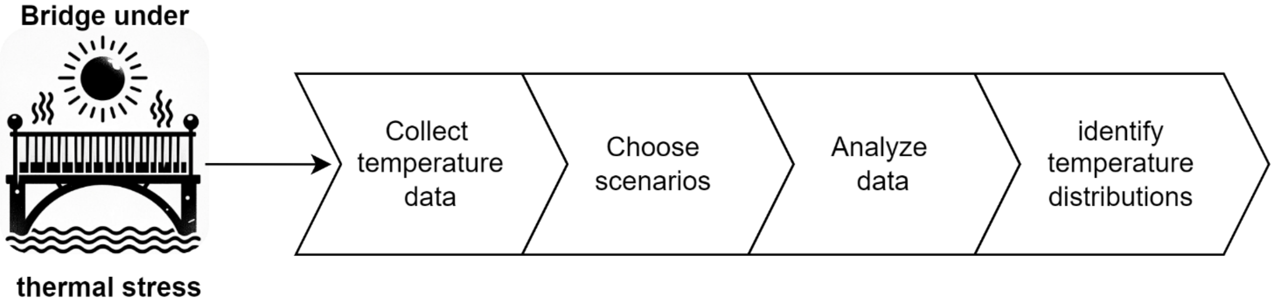


Figure 2: Temperature analysis process.

3.1 Acceleration analysis

Structures including footbridges are prone to various loads from users such as pedestrians and cyclists. Whilst the users are enjoying the path across the bridge, whether walking, cycling or even jumping. The footbridge bridge on the other hand, is vibrating as a response to the forces induced by the users. Different activities cause different types of vibration frequencies. Each with specific magnitude and acceleration, affecting the dynamics of the bridge. At the same exact time the bridge may be affected by other environmental conditions such as thermal stresses. Therefore, it is essential to analyze those vibrations, through different crossings, in relevance to chosen temperature scenarios.

Figure 3 illustrates the steps taken for the acceleration analysis. First, the vibrations are detected by the acceleration sensors installed in different known locations of the footbridge. Raw acceleration data of different crossings are collected, corresponding to chosen temperature scenarios. The raw acceleration data are initially demonstrated as time domain plot. However, due to the complex nature of the time domain plot. It is hard to identify the frequencies desired. The time domain is then transformed to frequency domain. Through the application of fast Fourier Transformation (FFT), the spectrum of the frequencies, composing the vibration signals is revealed, figure 4. The frequency is represented by power spectral density plot (PSD)

Moreover, Welch's method is used in order to clearly identify the bridge natural frequencies that need to be assessed. By estimating the power spectral densities (Kromanis, Elias, 2022). Figure 5 shows the translation of time domain structural response plot into a PSD plot identifying the dominant peaks. The dominant peaks in a PSD plot refer to the natural frequency of the bridge. The frequency (f) is identified by the equation $f = \frac{K.Fs}{N}$, k represents the number of cycles within the time period, N represents the FFT number and Fs represents the sampling frequency. According to Nyquist theorem, the data was sampled at a rate of 1000 samples per second, ensuring accuracy and relevancy through the process of the data analysis.

Furthermore, a PSD plot presents different peaks of natural frequencies depending on the activity being carried out on the bridge. The range of walking frequencies for a pedestrian footbridge lies between 1.6 to 2.4 Hz (Gheitasi et al., 2016). This range covers several pedestrian frequencies, such as walking, jogging, and jumping. Taking this into consideration, the analysis may not show clear results due to overlapping of data. Therefore, only the cyclists' crossings are determined.

Finally, the natural frequency peaks are visualized to corresponding temperature scenarios in order to assess any shifts. As temperature variation tends to affect the structure natural frequencies resulting in shifts in its natural frequency.

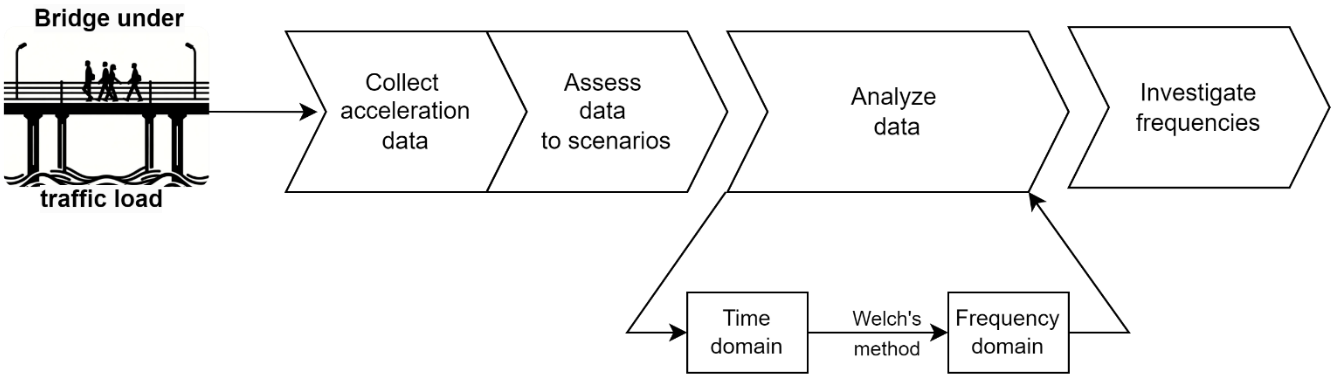
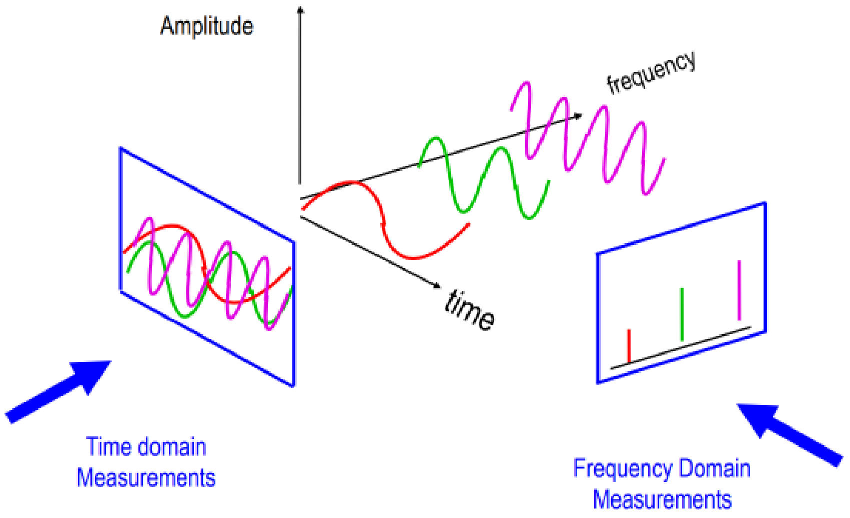


Figure 3: Acceleration analysis process



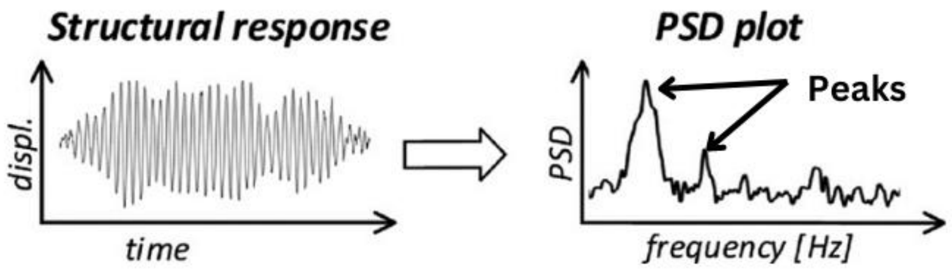


Figure 5: Time domain to Frequency domain, (Kromanis, Elias, 2022).

4 Results

This section of the paper will demonstrate the outcomes of the research. Firstly, by introducing the case study of the UT campus footbridge as a structure and identifying the sensor's location. Following that, the results of the temperature analysis will be illustrated along with other results from acceleration analysis. Finally, the temperature analysis will be correlated with the acceleration analysis.

4.1 UT Campus footbridge: Case study

The UT Campus footbridge is a 27 meters long bridge that was introduced to the public around the 1980s. Located at the University of Twente, the footbridge connects the Hogekamp (east) and the football field (west) across a pond. Figure 6 identifies the geographical location of the bridge.

Figure 6: UT Campus footbridge connecting to the west-side(upper diagram) and the geological location (lower diagram).

In order to analyze the data of the footbridge accurately, it is essential to understand the exact dimensions and structure of the footbridge, in addition to the sensor's locations on the bridge itself. The bridge contains three 27 meters long IPE600 steel girders with 80x80x55HS horizontal bracings. Adding to that, the bridge is covered with D40 hardwood oak timber decking and post with handrails. The UT Campus footbridge is monitored by different sensors. However, in the scope of the study, only the temperature and acceleration sensors are used in collecting the necessary data. It is essential to identify the locations of the sensors on the bridge to accurately assess the effect of temperature on the dynamics of the footbridge. Figure 8 provides a detailed illustration of the bridge's structure through a plan view and a cross-section drawing of the bridge. In addition, to the exact locations of the temperature and acceleration sensors, which are distributed on two of the three girders on the bridge. Girder A contains all the even numbered temperature and acceleration sensors, while Girder C contains the odd numbered sensors.

In the scope of investigating the footbridge dynamic response to changing temperatures. The sun is a main factor affecting the temperature of the UT Campus footbridge; therefore, it is essential to identify the path of the sun across the footbridge. Figure 7 shows that the sun is more dominant on the south-west side of the bridge during the day. However, that does not necessarily mean that only the southwest side is directly affected by sun on sunny days. The UT Campus footbridge is located near a tall building as well as being surrounded by trees, which affect the sun exposure on different locations of the bridge.

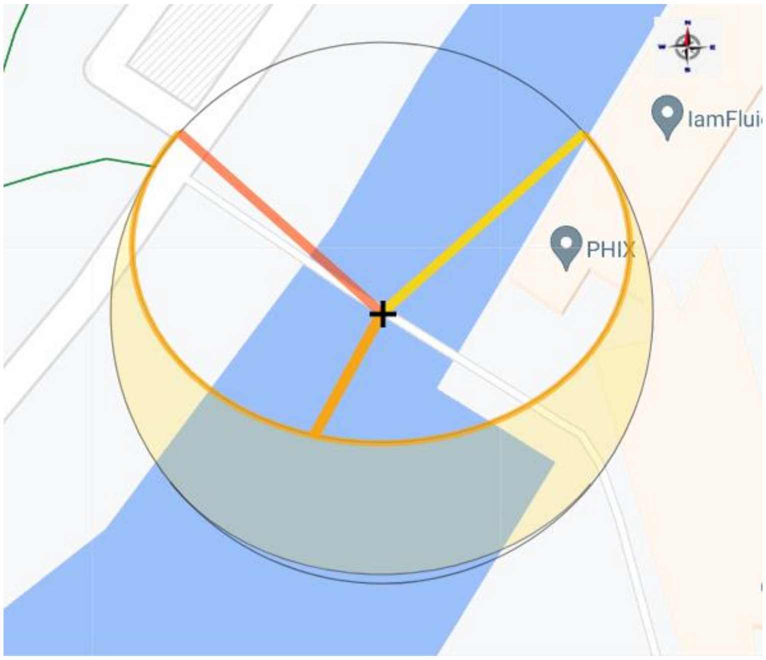


Figure 7: Sun path across UT Campus footbridge

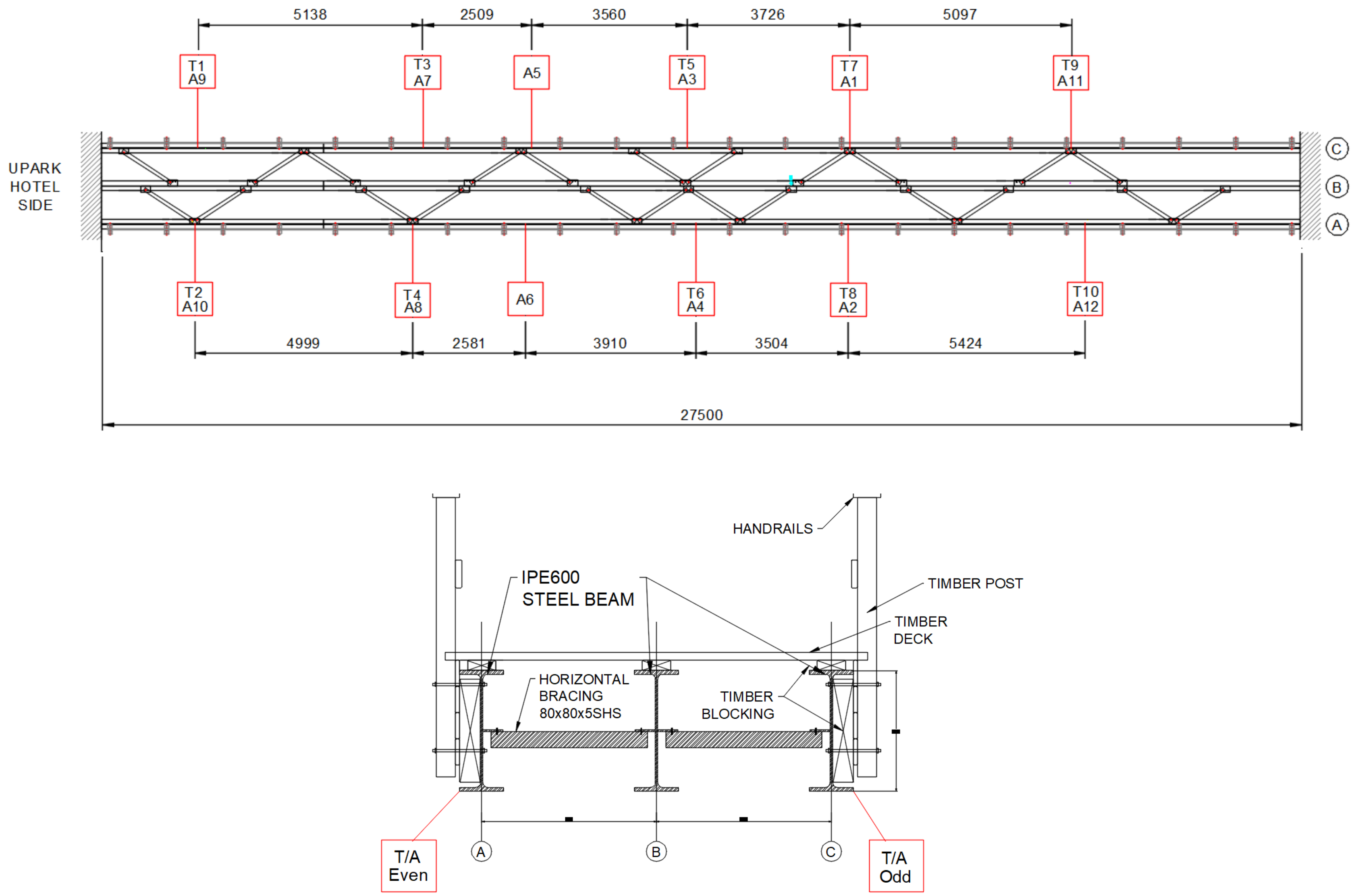


Figure 8: Plan view (upper diagram) and cross-section (lower diagram) of the UT Campus footbridge scale 1:100

4.2 Temperature analysis

This section presents an analysis of the data collected by the temperature sensors implemented on the UT campus footbridge, which captures the thermal response. The temperature history is shown in figure 9, illustrates the temperature data collected by all temperature sensors over the period starting Feb 2023 until December 2023. However, it is rather complex therefore in order to accurately analyze the temperature distributions. Eleven scenarios were chosen to cover and summarize most of the temperature distributions occurring on the footbridge. The scenarios consider different environmental conditions such as cloudy and sunny days under which the bridge was investigated. Moreover, the scenarios spot the light on abnormal temperature sensors reactions, at several temperatures and times. Where some temperature sensors have higher peaks than others at the exact same time and under the exact same conditions, however at different locations on the bridge. An example of those chosen scenarios is shown in figure 10.

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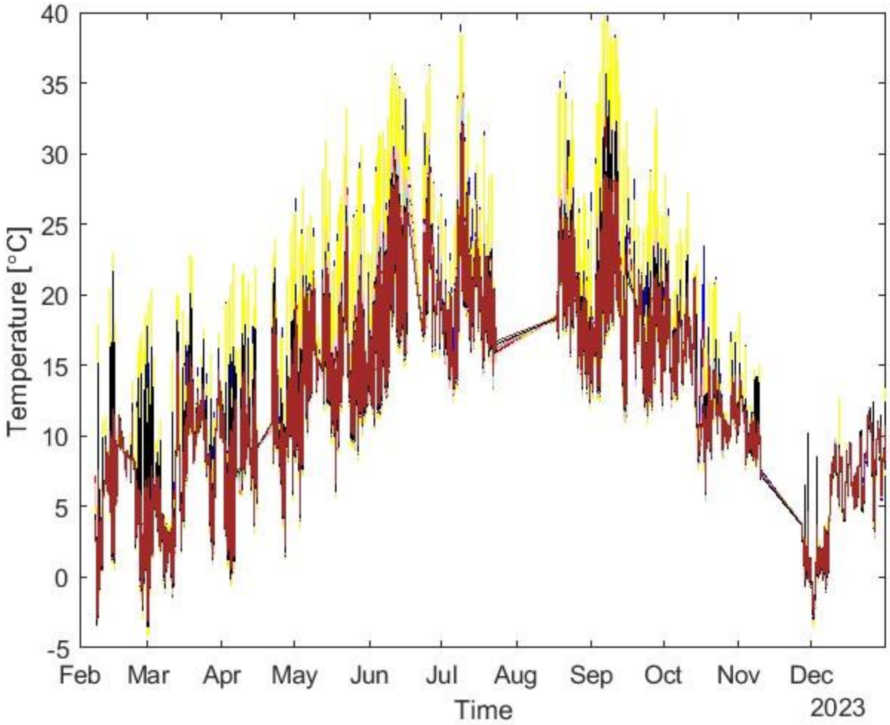


Figure 9: Temperature history

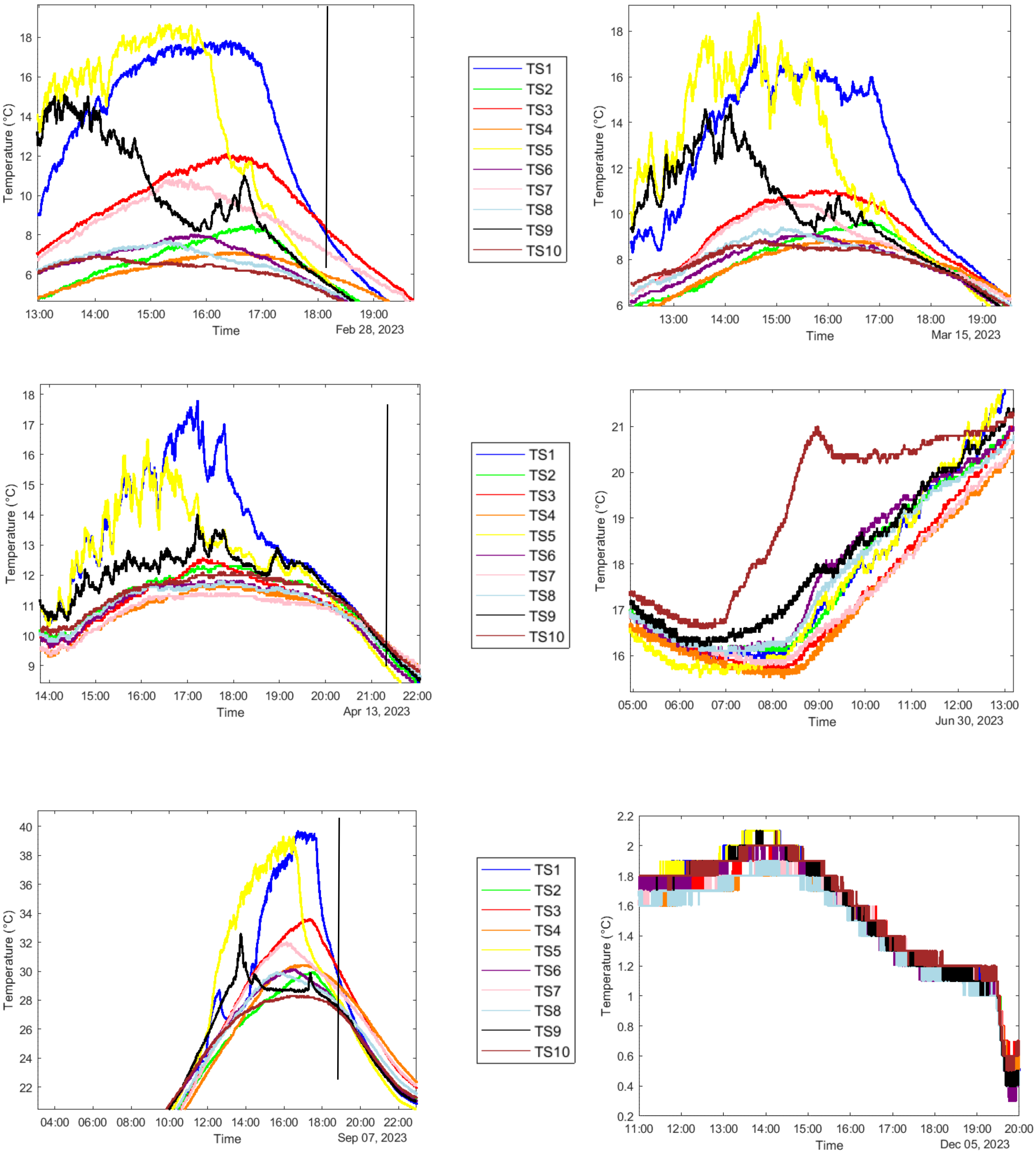
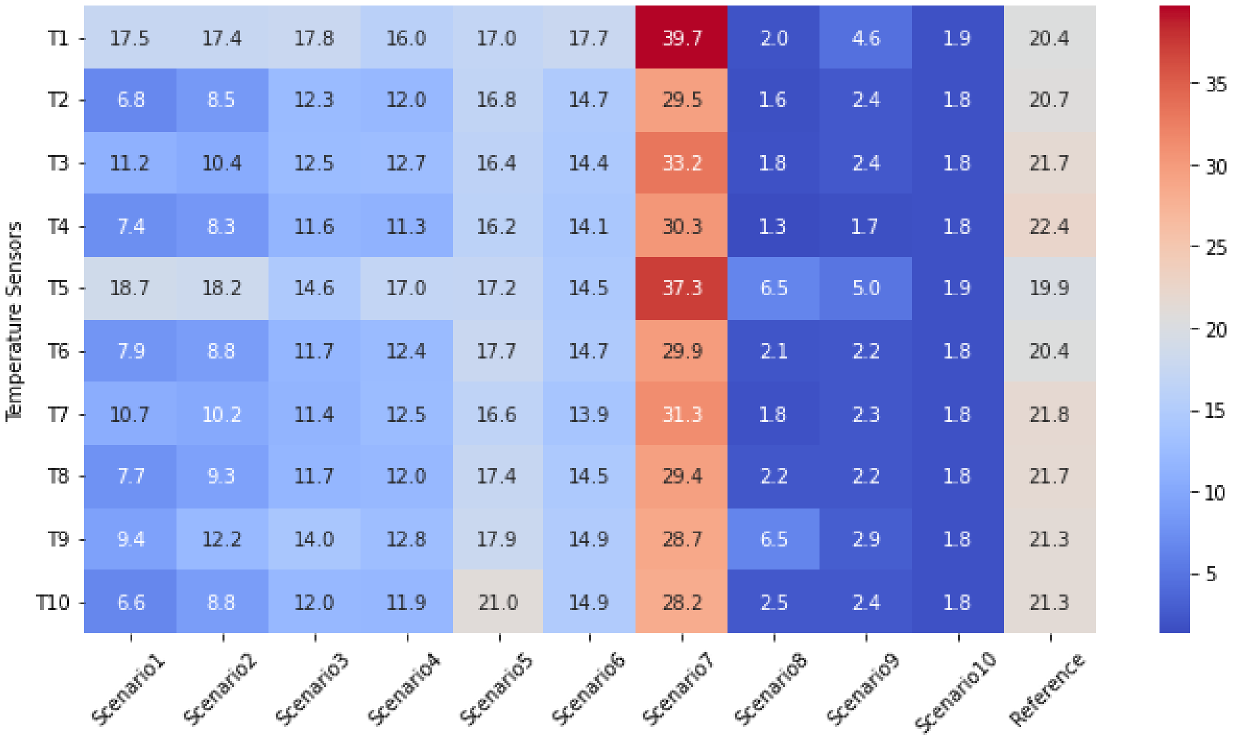


Figure 10: Measurement of temperature sensors for different scenarios.

After viewing daily temperature variations for each scenario, temperatures were collected at a specific time and assigned in a table for further analysis. A heatmap and a box plot were used to visualize the data detected by the sensors across 11 different scenarios including a reference scenario, offering unique insights about temperature variations. Figure 11 illustrates a color-coded matrix of temperature values in a table for which each cell represents temperature recoded by a sensor during a specific scenario, showing dark red cells which indicate higher temperatures and blue cells reflect low ones. Therefore, simplifying the visualization of the temperature variations, in different scenarios and across the ten sensors simultaneously, for example looking at the reference scenario, it can be concluded that all temperature sensors readings were similar in values which reflects a uniform distributed temperature across the bridge at that specific time. However, investigating scenarios such as 7 which was recorded in a hot day, one can deduce that sensors T1 and T5 gave much higher readings when compared to the other sensors. Similarly, on a cold day such as scenario 8, T5 and T9 recorded a temperature of 6.5 degrees Celsius, while the rest of the sensor's readings were an average of 1.8 degrees.



	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6	Scenario7	Scenario8	Scenario9	Scenario10	Reference
T1	17.5	17.4	17.8	16.0	17.0	17.7	39.7	2.0	4.6	1.9	20.4
T2	6.8	8.5	12.3	12.0	16.8	14.7	29.5	1.6	2.4	1.8	20.7
T3	11.2	10.4	12.5	12.7	16.4	14.4	33.2	1.8	2.4	1.8	21.7
T4	7.4	8.3	11.6	11.3	16.2	14.1	30.3	1.3	1.7	1.8	22.4
T5	18.7	18.2	14.6	17.0	17.2	14.5	37.3	6.5	5.0	1.9	19.9
T6	7.9	8.8	11.7	12.4	17.7	14.7	29.9	2.1	2.2	1.8	20.4
T7	10.7	10.2	11.4	12.5	16.6	13.9	31.3	1.8	2.3	1.8	21.8
T8	7.7	9.3	11.7	12.0	17.4	14.5	29.4	2.2	2.2	1.8	21.7
T9	9.4	12.2	14.0	12.8	17.9	14.9	28.7	6.5	2.9	1.8	21.3
T10	6.6	8.8	12.0	11.9	21.0	14.9	28.2	2.5	2.4	1.8	21.3

Figure 11: Color-coded matrix across 11 scenarios

Moreover, a box plot which represents the central tendency and IQR of each temperature sensor across the scenarios, this plot referred to as figure 12, clarifies and confirms the response of each sensor to temperature. Taking T1 and T5 as an example to compare, assessing the median line, it can be concluded that T1 records higher temperatures than T5. Moreover, the IQR and the whiskers shows that T1 records broader range of temperatures compared to T5.

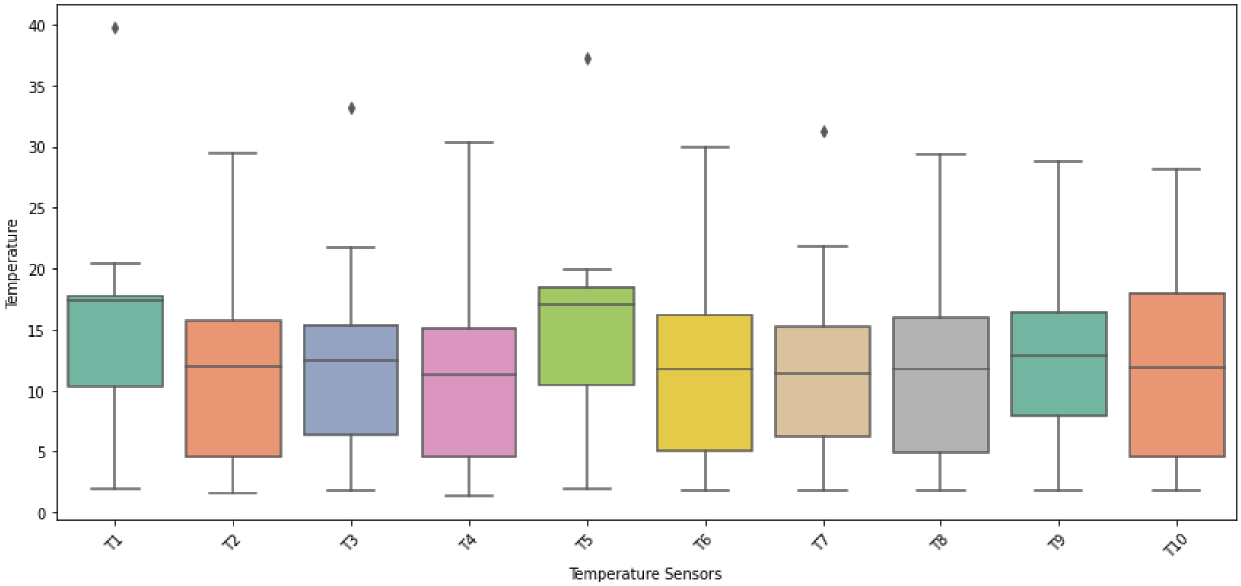


Figure 12: Box plot for sensors (T1-T10)

In conclusion, this analysis reveals critical insights about the thermal dynamics throughout the scenarios which reflects on the perceiving of the temperature by the bridge as a structure. Adding to that, the analysis spot various distributions of temperature across the bridge, therefore affecting different parts of the bridge, this is shown in figure 13 below, possibly because of the UT campus footbridge location and considering the sun path across it and being blocked by a high building such as campus 053 which keeps sensors T4 and T2 in shade throughout the day unlike sensors such as T1 and T5 that are more exposed to the sun .

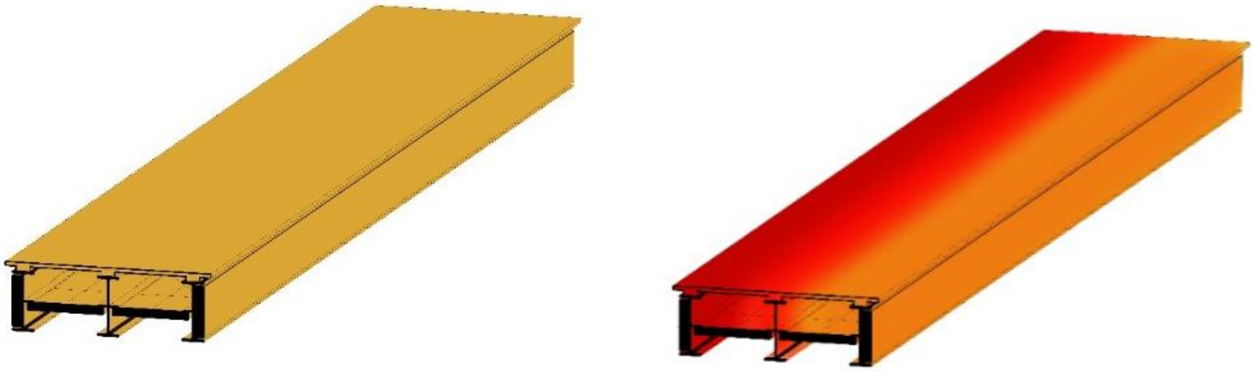


Figure 13: Temperature distribution of the UT Campus footbridge on a cloudy day (left) and on a sunny day (right)

4.3 Acceleration-temperature analysis

The dynamic response of the UT Campus footbridge is assessed through analzying the data collected by the acceleration sensors on the UT Campus footbridge. The analysis focus on the the dominant peaks initiated by the cyclists crossing the footbridge, which represents the bridge's natural frequencies.

The time domains of 8-9 seconds were used to identify the cyclists crossing apart from other crossing activities on the UT Campus footbridge. As it represents the time taken to cross the UT Campus footbridge, which has a span of 27 meters long, on a speed of around 11-12 km/h. the complex nature of the time domain makes it difficult to identify the any frequency peaks. Therefore, the Fast Fourier Transform (FFT) and Welch's method were implemented in order to identify the dominant frequency of the corresponding time domain on a PSD plot. Figure 14 show the time domain and its corresponding PSD plot identifying the dominant peak of the one of the chosen crossings. The same procedure were applied to 6 crossing scenarios at different dates and times to accurately identify the natural frequency of the footbridge. This is shown in figures 15 – 20.

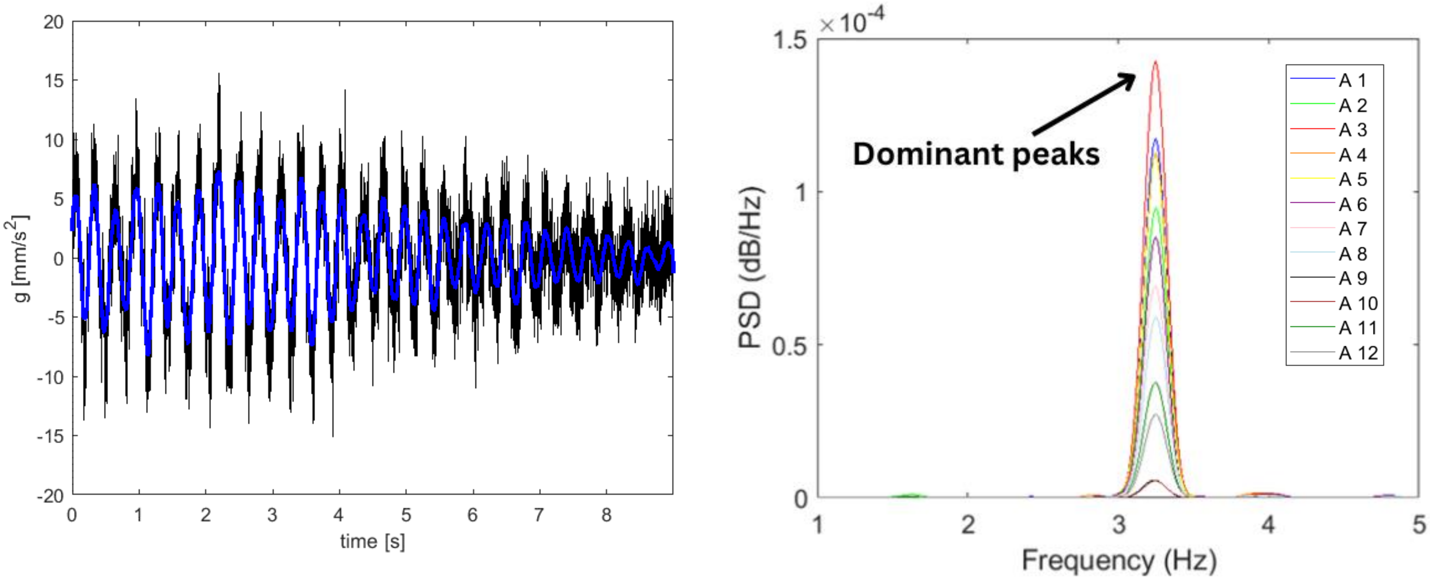


Figure 14: Time domain Vs frequency domain for crossing 1

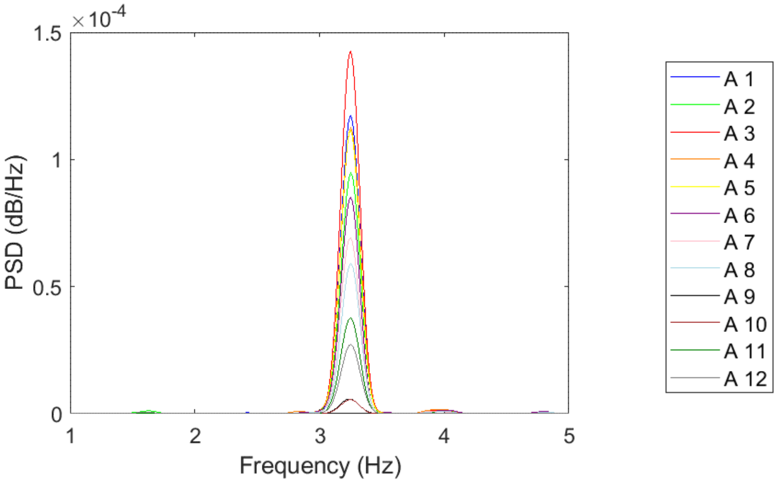


Figure 15: Crossing 1

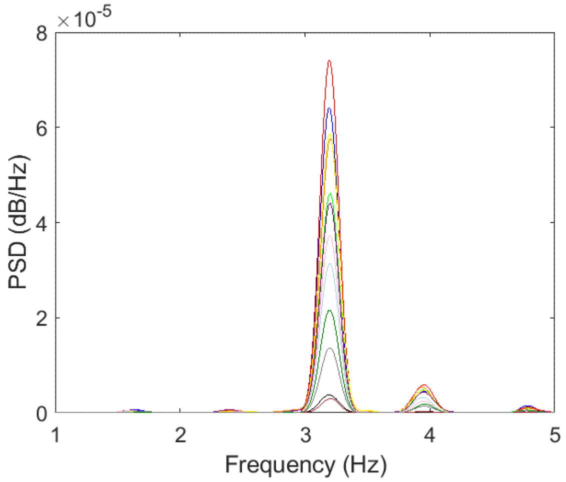


Figure 16: Crossing 2

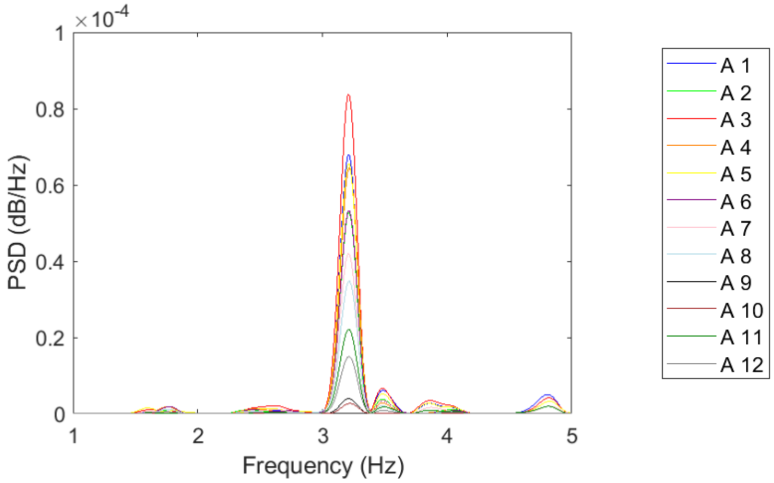


Figure 17: Crossing 3

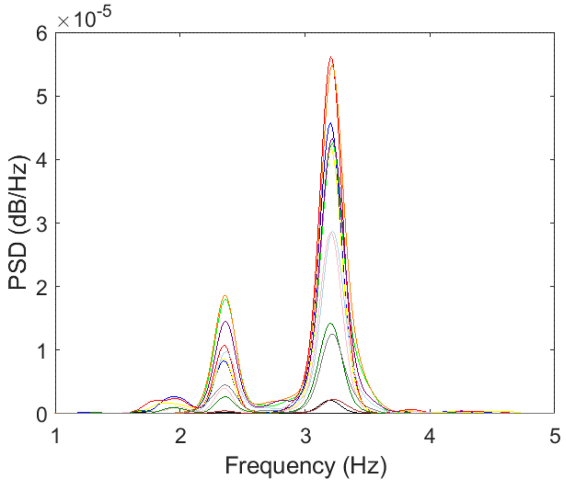


Figure 18: Crossing 4

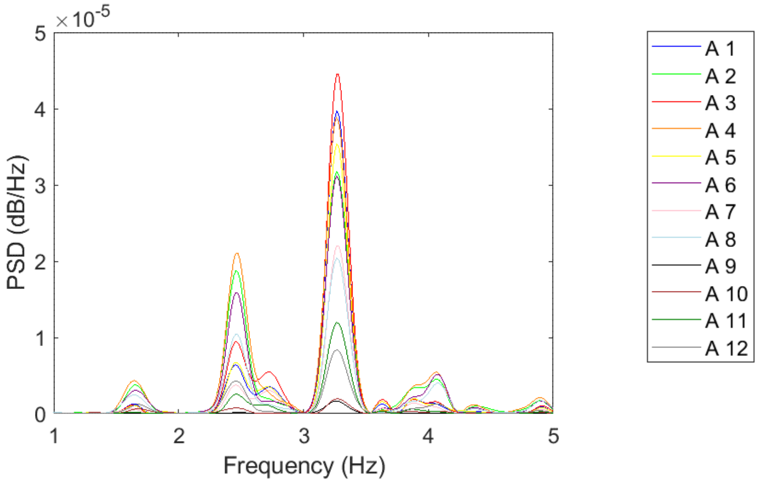


Figure 19: Crossing 5

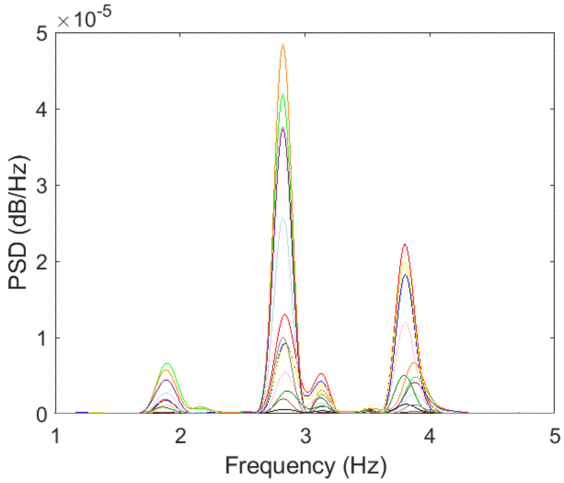


Figure 20: Crossing 6

From the figures showing the crossings chosen, the peaks recorded by each acceleration sensor are collected in table 1. The chosen crossings corresponds to 6 temperature scenarios. Crossings 1 to 5 correspond to the temperature scenarios 1 to 5. However, crossing 6 corresponds to scenario 9 which is rather cold compared to the other five scenarios.

	Crossing 1	Crossing 2	Crossing 3	Crossing 4	Crossing 5	Crossing 6
A1	3.25	3.2	3.2	3.2	3.26	2.82
A2	3.25	3.2	3.2	3.22	3.26	2.82
A3	3.25	3.2	3.2	3.2	3.26	2.82
A4	3.25	3.2	3.2	3.22	3.26	2.82
A5	3.25	3.2	3.2	3.2	3.26	2.82
A6	3.25	3.2	3.2	3.22	3.26	2.82
A7	3.25	3.2	3.2	3.2	3.26	2.82
A8	3.25	3.2	3.2	3.22	3.26	2.82
A9	3.25	3.2	3.2	3.2	3.26	2.82
A10	3.25	3.2	3.2	3.22	3.26	2.82
A11	3.25	3.2	3.2	3.2	3.26	2.82
A12	3.25	3.2	3.2	3.22	3.26	2.82

Tabel 1: Peak frequency values in Hz recorder by acceleration sensors A1-12

The peaks collected from the acceleration sensors, ranges from 3.26 Hz which is the highest peak recorded to 2.82 Hz which is the lowest. The crossings 1 to 5 have a range of frequency of 3.2–3.26 Hz. Nevertheless, the lowest natural frequency peak was recorded only on crossing 6, which is identified corresponding to the temperature scenario with the lowest temperature. Line plot is used to plot both crossing frequencies and temperature variations in order to visualize the data. Figure 21 shows the temperatures recorded at the scenarios and the natural peaks for the cyclists crossing. It can deduct that for the scenarios 1 to 5 the natural peak was at its highest. In comparison to scenario 9 which had the lowest temperature as well as the lowest peak value. Indicating a shift in the natural frequency of the UT Campus footbridge in response to the cyclist crossing. Such shift, showing a decrease in frequency, can identify different load paths.

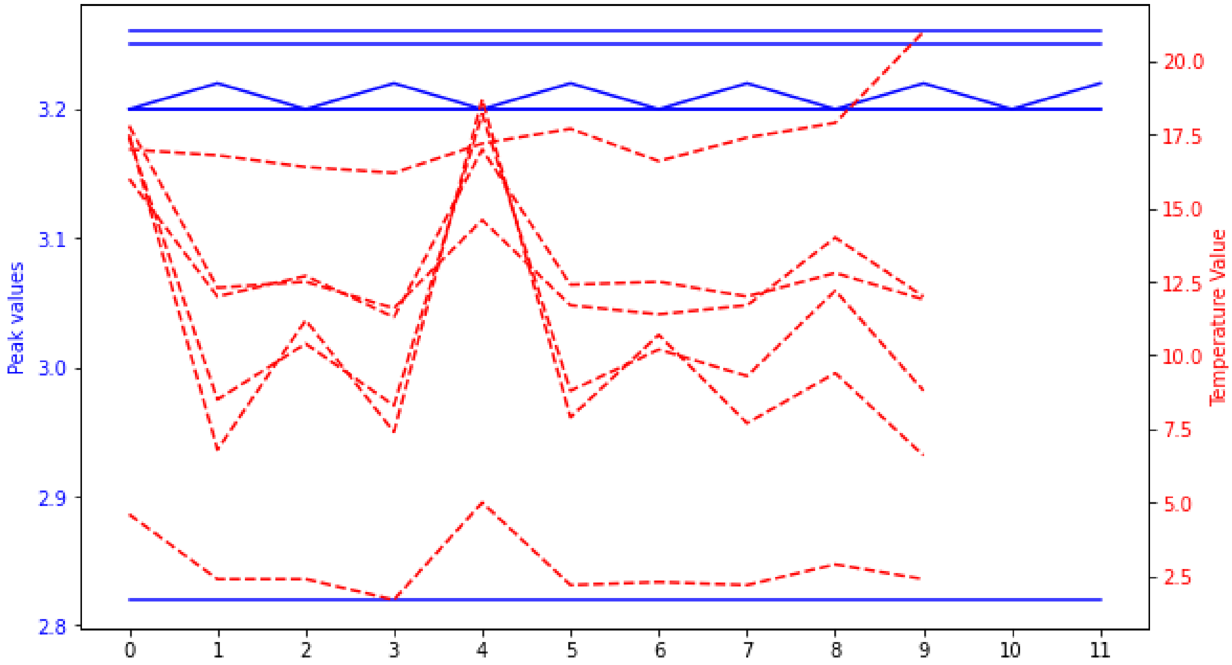


Figure 21: frequency peak crossing against temperature scenarios

In conclusion, this section showed how the acceleration data for the UT Campus footbridge were analysed. Firstly, by identifying the specific time domains to be chosen. Then using both Fast Fourier transformation (FFT) and the Welch's method to identify the dominant peaks for crossing. Six crossings were chosen corresponding to 6 temperature scenarios, the plots for each crossing were identified along with a table including all the peak values for the acceleration sensors. Further a plot showing the peak frequencies plotted in relation with the temperature scenarios.

4.4 Discussion

Investigating the effects of temperature distributions on the dynamic response of the UT Campus footbridge has presented various key findings. This investigation contribute to the understanding of SHM and the influence of such environmental conditions on civil structures. Through the use of contact-based sensor data collected and an integrated SHM methodology, parameters such as temperature and acceleration were analysed. Taking a step into the investigation of distributed temperature effects on the structural dynamics of footbridges.

The study indicates the temperature distributions for the UT Campus footbridge, therefore affecting different parts of the bridge. As temperature variation has the ability to change the stiffness of materials and thus the boundary conditions of a system

(Mikolaj, 2021; Catbas, Susoy, & Frangopol, 2008). The acceleration analysis assessed the peak (natural) frequency of cyclists crossing the UT campus footbridge. The natural frequency was found to shift in response to the change in temperature. temperature variation can cause the first mode's natural frequency to vary (Doebling & Farrar, 1997; Askegaard & Mossing, 1998). Moreover, this shift indicates a frequency decrease.When damage increases the natural frequencies tend to decrease, as damage magnitude is proportionate to stiffness (Farrar, et al., 1996).

The research study has demonstrated the impact of temperature variations on the dynamic behaviour of the UT Campus footbridge, strengthening the significance of considering environmental factors in the design, and monitoring of civil engineering structures. However, facing several limitations and challenges:

- The UT Campus footbridge was analyzed only under the effect of temperature as an environmental, however, other conditions such as humidity and wind can influence the analysis.
- The analysis was done through data collected over a period of one year only, however, to conduct a more reliable analysis data over several years should assessed.
- Few data collected by the temperature sensors showing temperature distributions were found relevant to be analysed and form scenarios.
- The acceleration temperature analysis was limited to the number of crossings found per temperature scenario. As scenarios of high temperature was not assessed in the acceleration analysis. Several crossing data were needed in order to visualize more frequency peaks.
- Further analysis using mode shapes can give deeper illustration and assessment for induced damage.

5 Conclusion

The research explored and investigated, how temperature variations affect the dynamic response of the UT Campus footbridge. Through, thoroughly analysing both temperature and acceleration data, collected from the sensors installed on the UT Campus footbridge. Correlating the temperature and acceleration analysis, opened a pathway into discovering the interplay between environmental factors and structural behaviour. Therefore, concluding valuable insights into structural health monitoring.

The research paper conducted a robust literature review concluding comprehensive insights about SHM, structural dynamics and bridge response to temperature variations. In addition to the methodology illustrating the steps taken in order to achieve intended results of the research paper. Through the use of the reviewed literature. Temperature analysis showed the effect of temperature on different parts of the bridge, through analysing the data collected by the temperature sensors implemented on the bridge. Those scenarios were accompanied by cyclists crossing scenarios that shows the UT Campus footbridge response by assessing its natural frequency.

The results for the temperature analysis concluded that the temperature on the south-west side of the bridge is higher than the temperature recorder on the northeast side of the bridge. Through assessment of the temperature sensors, such temperature distributions were captured. Moreover, the analysis of acceleration-temperature highlights the interrelationship between temperature change and the dynamic behaviour of the bridge, through a vibration assessment. The analysis of the 6 cyclists crossing resulted in identifying the UT Campus footbridge natural frequency to be of the range 3.2 – 3.26 Hz. In addition, the effect of temperature changes on the bridge’s natural frequency, indicated by the shift of natural frequency range, decreasing to a value of 2.82 Hz.

Such insights suggest the importance of considering distributed temperature effects on the structure in further research. As well as considering the limitation that the research was conducted on the UT Campus footbridge under the effect of temperature fluctuations only. Therefore, further studies encompassing different bridge types, environmental conditions and the application of advanced predictive models should be assessed. In addition to further research, into integration between SHM and temperature effects. As well as a deeper investigation on the integrated effects on those vibration properties and the effect of the distributed temperature on structural dynamics.

In conclusion, this investigation into the effect of temperature distribution on the UT Campus footbridge vibration parameters. Contributing with valuable insights to the existing knowledge in civil engineering, particularly in the field of SHM and environmental impact assessment. However, with further research and deeper investigations to be conducted.

References

Avnon, R., 2022. Smartphone-Based Vibration Analysis for Bridge Health Monitoring (Bachelor's thesis, University of Twente).

Askegaard, V., Mossing, P., 1998. Long term observation of RC-bridge using changes in natural frequency. Nordic Concrete Research, 20-27.

Behkamal, B. et al. (2023) 'Investigation of temperature effects into long-span bridges via hybrid sensing and supervised regression models', Remote Sensing, 15(14). https://doi:10.3390/rs15143503.

Baus, U. & Schlaich, M., 2008. Footbridges: Construction, Design, History. Berlin, Boston: Birkhäuser. https://doi-org.ezproxy2.utwente.nl/10.1007/978-3-7643-8222-3.

Ceravolo, R., Coletta, G., Miraglia, G., Palma, F., 2021. Statistical correlation between environmental time series and data from long-term monitoring of buildings. Mechanical Systems and Signal Processing, 152, 107460. https://doi.org/10.1016/j.ymssp.2020.107460.

Catbas, F. N., Susoy, M., Frangopol, D. M., 2008. Structural Health Monitoring and Reliability Estimation: Long Span Truss Bridge Application With Environmental Monitoring Data. Engineering Structures, 30(8), 2347-2359. https://doi.org/10.1016/J.ENGSTRUCT.2008.01.013

Doebling, S. W., Farrar, C. R., 1997. Using statistical analysis to enhance modal-based damage identification. In: Proceedings of DAMAS 97, University of Sheffield, UK, pp. 199-210.

Farrar, C. R., Baker, W. E., Bell, T. M., Cone, K. M., Darling, T. W., Duffey, T. A., Migliori, A., 1996. Dynamic characterization and damage detection in the I-40 bridge over the Rio Grande. Los Alamos: U.S. Department of Energy. https://doi.org/10.2172/10158042

García, D.A., Rosales, M.B., Sampaio, R., 2019. Dynamic behaviour of a timber footbridge with uncertain material properties under a single deterministic walking load. Struct. Saf., 77, 10–17.

Gheitasi, A., Ozbulut, O. E., Usmani, S., Alipour, M., Harris, D. K., 2016. Experimental and analytical vibration serviceability assessment of an in-service footbridge. Case Studies in Nondestructive Testing and Evaluation, 6, 79-88. https://doi.org/10.1016/j.csndt.2016.11.001

Goulet, J. A., Kripakaran, P., Smith, I. F., 2015. Multimodel structural performance monitoring. Journal of Structural Engineering.

Hashimoto, K., Shiotani, T., Mitsuya, H., Chang, K. C., 2020. MEMS Vibrational Power Generator for Bridge Slab and Pier Health Monitoring. Applied Sciences, 10(22), 8258. https://doi.org/10.3390/app10228258

Huston, D., 2019. Structural Sensing, Health Monitoring, and Performance Evaluation. 1st ed. Series in Sensors. Routledge.

Kromanis, R. and Elias, S., 2022. Measuring dynamic response of the Wilford Suspension Bridge with a vision-based measurement system: A case study', Lecture Notes in Civil Engineering, pp. 280–289. https://doi:10.1007/978-3-031-07254-3_28.

Kromanis, R. and Kripakaran, P. 2014 Predicting thermal response of bridges using regression models derived from measurement histories. Computers & Structures, 136, pp. 64–77. https://doi:10.1016/j.compstruc.2014.01.026

Marchenko, A., 2023. Parametric Study of Temperature Effects on Traffic-Induced Response for Bridge Structural Health Monitoring (master's thesis, University of Twente).

Matarazzo, T., Vazifeh, M., Pakzad, S., Santi, P., Ratti, C., 2017. Smartphone data streams for bridge health monitoring. Procedia Engineering, 199, 966–971. https://doi.org/10.1016/j.proeng.2017.09.203

Salawu, O., 1997. Detection of structural damage through changes in frequency: a review. Engineering Structures, 19(9), 718–723. https://doi.org/10.1016/s0141-0296(96)00149-6

Sohn, H., 2006. Effects of environmental and operational variability on structural health monitoring. Philosophical Transactions of The Royal Society A, 364(1838), 539-560. https://doi.org/10.1098/rsta.2006.1935

Sony, S., Laventure, S., Sadhu, A., 2019. A literature review of next-generation smart sensing technology in structural health monitoring. Structural Control and Health Monitoring, 26(3), e2321. https://doi.org/10.1002/stc.2321

Tadeu, A., Romero, A., Bandeira, F., Pedro, F., Dias, S., Serra, M., Galvin, P., 2022. Theoretical and experimental analysis of the quasi-static and dynamic behaviour of the world's longest suspension footbridge in 2020. Engineering Structures, 253. https://doi.org/10.1016/j.engstruct.2021.113830

Tibaduiza Burgos, D. A., Gomez Vargas, R. C., Pedraza, C., Agis, D., & Pozo, F., 2020. Damage Identification in Structural Health Monitoring: A Brief Review from its Implementation to the Use of Data-Driven Applications. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7038520/

Turk\'ow,M.,2022.Investigating limitations of computer vision structural health monitoring: a case study on the UT campus footbridge. http://essay.utwente.nl/93547

The Constructor, 2021. What is Structural Health Monitoring in Civil Engineering? Retrieved from https://theconstructor.org/digital-construction/structural-health-monitoring-civil-engineering/554160

Zolghadri, N., Halling, M. W., Barr, P. J., Masters, N. F., Foust, N., 2015. Effects of Temperature on Bridge Dynamic Properties.