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Modeling the effects of temperature gradients on the dynamic properties of a girder

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Preface

This thesis marks the end of the 3 years I have spent studying Civil Engineering at University of Twente. The project was done under the supervision of dr. ing. Roland Kromanis and it aims to give further insight into how temperature gradients influence the dynamics of structures.

I want to extend my gratitude to dr. ing. Roland Kromanis for guiding me through the process of writing this thesis and for his help in furthering my knowledge on various subjects such as Finite Element Modeling and structural dynamics. His insight facilitated the progress of the thesis and gave me a new insight into the role of civil engineers in the day to day life of everyone.

I would also like to thank my friends who have supported me throughout the 3 years I have spent in Enschede and especially during the last 2 months. Without their help, this thesis would not be possible, and for that I am eternally grateful.

Ana-Valeria Cracanuța
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Abstract

Structural Health Monitoring (SHM) aims to detect and locate damage in civil structures by monitoring and analyzing their structural responses over time. One of the methods of damage detection is the vibration based approach. It relies on changes in modal parameters, which occur in the event of damage introduction. But modal parameters can also be affected by environmental factors. This thesis investigates the impact of certain temperature gradient assumptions on the reliability of vibration based damage detection.

A Finite Element Model (FEM) of a simply supported HE 200B steel girder was subject to a coupled-field analysis which involved a pre-stressed modal analysis given the results of a transient thermal analysis. Two thermal loading scenarios were investigated: spring and winter. They involved hourly data on sun irradiance and ambient temperature, for two separate days. The study compared the effects of the realistic temperature distributions with those of a uniform temperature on the frequencies of the first three modes of the girder. Lastly, damage was introduced to evaluate whether its effects on dynamics are more or less pronounced than those of temperature.

The results show that the assumption that the girder has the same temperature as the ambient introduces error in modal frequency computing, especially for mode 1 (lateral) and mode 2 (torsional). Meanwhile, mode 3 (vertical) remained insensitive to them. But the relative errors followed the same pattern as the ambient temperature. When structural damage was introduced, the thermal effects either masked or exacerbated its effects depending on the studied mode.

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1 Introduction

Throughout their life, civil engineering structures (buildings, bridges, roads, etc.) undergo multiple types and intensities of loadings, which, in turn, lead to gradual deterioration. In order to prevent failure, regular maintenance and checks have to be performed. This process is often very costly both in the financial and temporal sense, especially for massive structures, which require a highly specialized set of engineering teams. For example, a case study of a highway bridge in Italy, with a span of 30 m, showed that its failure could result in €84.6 million in traffic, social, and construction costs (Contardi and La Fortezza 2024). This problem has led to the development of the field of Structural Health Monitoring (SHM), which allows for structures to be monitored remotely and damage to be detected faster without the need for much human labor. With the help of SHM systems, inspection and operating costs of bridges can be reduced by 25% and the traffic related costs can be lowered by 30% by minimizing the number of site inspections (Comisu et al. 2017).

SHM is mainly concerned with the observation and analysis of systems by periodically measuring changes in their response to external factors. It has the goal of ensuring that engineering structures are safe to use, but also of locating issues in an effective manner. SHM systems rely on a network of sensors that collect data on a structure (its temperature, frequency, strain, load levels) (Brownjohn 2007). There are a few ways of detecting damage in SHM, but the one on which this project focuses on is vibration based damage detection. It uses a number of accelerometers that record the frequency at which a bridge vibrates as a result of external excitation. If said frequency deviates too much from its natural value it can be assumed that damage is present in the structure. Certain environmental factors can influence the response of a civil structure (Alampalli 1998). For example, the roughness of a bridge's deck can lead to modal changes which usually indicate damage, even though structurally there are no failures. This leads to unnecessary interventions, or in the opposite scenario certain damages could go undetected as a result of unjust data interpretation.

It is of great importance to understand how temperature, wind, humidity, etc. influence the structural properties of objects. Temperature has been proven to be one of the most influential factors, since its uniform distribution along the depth and surface is not always linear (Potgieter and Gamble 1989) and leads to frequency changes in the studied object. Previous studies have shown the inverse relationship between frequencies of structures and their temperature (G.-D. Zhou and Yi 2014), so it has to be considered when sensor networks are installed and also in the data processing step. Civil engineering structures are exposed to varying sources of heat in intensity and location, the temperature distributions can become complex (Biliszczuk et al. 2021).

A tool that has helped understanding behavior of structures is Computer Aided Engineering (CAE), which allows engineers to simulate complex phenomena in a time-efficient way, compare theoretical and real-life data, understand which factors influence certain events, etc. One CAE method is the Finite Element Method, which works by splitting a complex system into smaller elements. Such virtual models are also widely used in data analysis, which, in turn, leads to better comprehension of natural phenomena. SHM takes advantage of this technology for detecting damage, since a Finite Element Model (FEM) can serve as a proxy for an undamaged structure. A FEM can be used for understanding the underlying reasons for a structure's behavior, without the need of a physical model (Liu, Z. Chen, and T. Zhou 2012;Xia, Xu, et al. 2011;Abid et al. 2017). A FEM can use the data from temperature sensors to compute the modal parameters of the studied object in relation to it, but there exists the problem of model accuracy, since, as said before, sensor data can be quite limited which leads to certain errors in the model.

1.1 Research aim and objectives

The aim of this research project is to give insight into the relevance of heat gradients for SHM by comparing the results of a multi field analysis of a girder subjected to a heat source varying in time and space given different assumptions about the temperature distribution. The main question that needs to be answered: Is the assumption of uniform temperature distribution along the length of an element appropriate for vibration based damage detection?

The answer is explored by modeling and comparing the changes in modal frequency given two main assumptions: uniform temperature along the length of the girder and the actual gradient due to the heat source. Consequently, the effect of damage are also be studied. The goals of the thesis are:

- Investigate the relationship between temperature and dynamic properties of structures.
- Build a Finite Element Model of a girder subject to a time and space variable heat source.
- Create scenarios of uniform and non-uniform temperature gradients along the length of the girder.

- Analyze the effect of the temporal-spatial temperature distributions on vibration parameters in different scenarios.
- Introduce damage in the structure and evaluate the amplitude of its effects compared to those of temperature .

1.2 Scope of study

The thesis explored the influence of temperature distributions on dynamic properties of civil engineering structures, within the context of vibration based SHM. It uses a FEM of a simply supported girder to study how varying thermal assumptions affect the reliability of modal frequency computing and consequently, comparing their effects to those of damage introduction.

Chapter 2 describes the theoretical background necessary to understand the study, covering principles of heat transfer, Finite Element Modeling and structural dynamics. Chapter 3 presents previous research done on the subject and identifies the gaps that this study aims to fill. The methodology is presented in chapter 4. The case study is presented in chapter 5 and it also includes the results of the model and a discussion which interprets them. The final chapter summarizes the findings and highlights the most important ones.

2 Background

The model involves a few steps: thermal analysis, modal analysis, and result interpretation. As such, the concepts of heat transfer, structural dynamics and finite element analysis have to be understood. A brief explanation is offered in this section.

2.1 Heat transfer

Heat transfer (or energy transport), according to the second law of thermodynamics, occurs when there are differences in temperatures (temperature gradients) between two connected mediums. The mechanisms through which this occurs are: convection (occurs in fluids due to its movements), conduction (energy transfer from one point of a solid to another due to temperature differences), radiation (heat loss or gain without the need of a physical medium).

2.1.1 Conduction

A relevant example that can help understand the process of conduction is a solid cube, which has temperature t_1 on one side and temperature t_2 on the other side. Given that $t_1 > t_2$ then temperature flows from the inner surface of the cube to the outer one according to formula 1. The schematization of the process can be seen in Figure 1.

$$q_x = -kA\frac{dt}{dx} \tag{1}$$

- q_x[W] - rate of heat transfer in x direction
- k [$\frac{W}{mK}$] - material property of thermal conductivity
- A [m^2] - surface area normal to heat transfer direction
- $\frac{dt}{dx}$ [$\frac{K}{m}$] - gradient of temperature in x direction

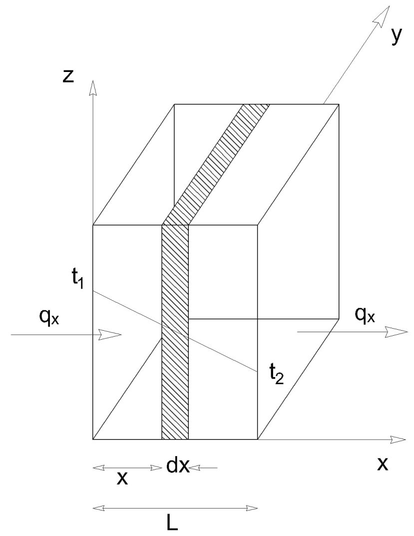


Figure 1: Heat flow across a solid

A more used unit of measurement for this phenomenon is the heat flux (q"$_x$), which is defined as the heat flow per unit area [$\frac{W}{m^2}$]. By dividing equation 1 by area (A) and integrating (assuming linear temperature variation), the formula for heat flux can be derived, where L[m] is the perpendicular length between the two heat sources.

$$q''_x = k\frac{t_1 - t_2}{L} \tag{2}$$

All the previous equations were given for a single x direction, but temperature can vary in all three coordinate directions: t=t(x,y,z,τ), where τ is time. As such, formula 3 is more general, where $\vec{\nabla}$ is the gradient of the scalar vector field.

$$\vec{q}'' = -k\vec{\nabla}t = -k(\vec{i}\frac{\delta t}{\delta x} + \vec{j}\frac{\delta t}{\delta y} + \vec{k}\frac{\delta t}{\delta z}) \tag{3}$$

A last remark is about the nature of the medium through which temperature flows. There are 3 types of mediums: isotropic (properties do not change along the direction), orthotropic (properties change in mutually perpendicular direction) and anisotropic (properties change in all directions). For the purposes of the project the materials are assumed to be isotropic.

2.1.2 Convection

Convective heat transfer refers to temperature changes due to fluid motion. In the context of this thesis, it refers to a solid (the girder) making contact with a moving fluid (the air), thus exchanging heat. But, due to the viscosity of the fluid, its velocity decreases as it approaches the solid, thus the velocity at the contact point can be considered 0. In this case, conduction laws can be applied, but since the temperature gradient of the fluid is highly dependent on its velocity, convection is still relevant in this case. The general formula is given by Newton's law of cooling:

$$q_c = hA(t_s - t_f) \tag{4}$$

- h [$\frac{W}{m^2K}$] - convection heat transfer or film coefficient
- A [m^2] - heat exchange surface
- t_s [°K] - solid temperature
- t_f [°K] - fluid temperature

h is usually further defined as a function of w [m/s] - fluid velocity, in this case it is given by the expression: $h = 1.16(10.45 - w + 10\sqrt{w})$ (Engineeringtoolbox 2025). Should be noted that this expression can only be used in cases where the velocity is between 2 and 20 m/s.

2.1.3 Radiation

Radiative heat transfer can happen regardless of the state of matter of the object, since at its core it is the release of electromagnetic waves. The Stefan-Boltzmann law determines the maximum flux at which radiation may be emitted from a surface and is given by equation 5.

$$q''_r = \varepsilon \sigma t^4 \tag{5}$$

- $q"_r$ [$\frac{W}{m^2}$] - maximum radiation flux
- ε [-] - emissivity factor $0 < \varepsilon \leq 1$
- σ [$\frac{W}{m^2K^4}$] - Stefan-Boltzmann constant $5.57*10^{-8}$

When talking about the radiation between 2 objects, it depends also on their geometry. More so, it is important to take into account that not all emitted radiation from an object 1 is intercepted by object 2, a transfer factor F_{12} is added to the equation which depends on emittances and geometry of the objects. As such, equation 5 can be rewritten as:

$$q_r = A_1 F_{12} \sigma (t_1^4 - t_2^4) \tag{6}$$

2.2 Structural dynamics

The field of structural analysis is concerned with how external loads influence structures and their components. A branch of it is structural dynamics, which aims to assess the behavior of systems under dynamic loading (varies over time). In this context, the main characteristics that describe a mechanical system are: natural frequency (rate at which a system vibrates in the absence of disturbance), natural mode shapes (deflection pattern associated with each natural frequency) and damping ratio (the rate of oscillatory energy dissipation). Since multiple studies have shown no definitive connection between the damping ratio and a system's temperature (G.-D. Zhou and Yi 2014), this characteristic is not further explored. Factors which affect dynamic characteristics are: geometry (and boundary conditions), stiffness, mass (or density).

In order to extract the dynamic properties of a system, a modal analysis has to be done.

$$[M]\{a\} + [K]\{u\} = \{0\} \tag{7}$$

Equation 7 represents the linear equation of motion for undamped vibration, where:

- M - mass matrix
- a - acceleration
- K - stiffness matrix
- u - displacement

Assuming the system undergoes harmonic motion (oscillation can be expressed using only one harmonic function, like sine or cosine), there are certain formulas with which the acceleration and displacement can be calculated. The resulting equation 8 is obtained by substituting a and u in equation 7. The solutions to equation 8 represent the frequency (ω) and the mode shape (ϕ) for the i^{th} mode of a structure.

$$([K] - \omega_i^2[M])\{\phi_i\} = \{0\} \tag{8}$$

This is a very idealized and simplistic way of doing a modal analysis, but it serves in understanding the core principles and the way in which the software undergoes such analyses. For the context of this research, since the object to be modeled is a simply supported beam, its first three vertical mode shapes are represented in Figure 2.

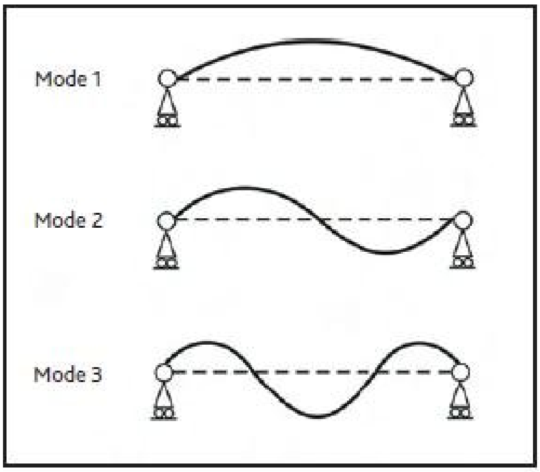


Figure 2: The first three bending modes of a simply supported beam (Willford and Young 2006)

2.3 Finite Element Analysis

FEA is a computerized method of predicting how an object of study reacts to physical effects based on calculations done using a FEM. It involves breaking down complex systems into smaller elements, called meshing. These elements are defined by their nodes, which are points in space determined by their coordinates. FEA is the process through which all the individual elements are rearranged into the initial system, but with new information. FEA allows the user to simulate a wide range of physical analyses, be it thermal, structural, acoustic or even a combination of several of them, without the need for extreme computational power and/or resources, which is especially useful for complex systems that cannot be easily evaluated. The basic steps are depicted in Figure 3.

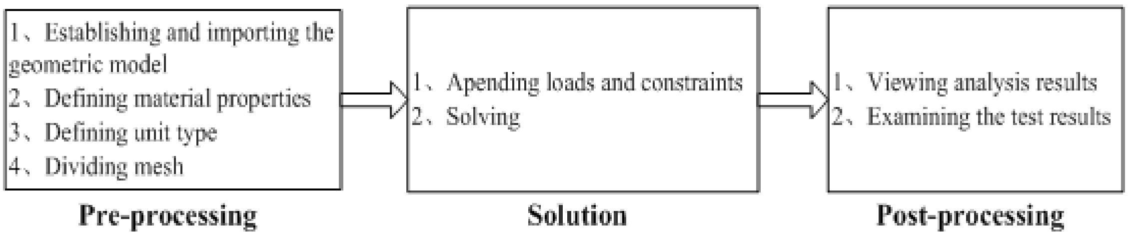


Figure 3: Basic steps of a simulation analysis (Wang 2022)

FEA is done in several steps. Firstly, the properties of the studied object have to be defined, such as its geometry, material properties, physical constraints and the medium in which it exists. Then, the user defines the type of elements to be used for the meshing depending on the type of analysis. Next step is the solution step, in which external loads are applied and their effect on the object of the study is computed. Last step is where the user can extract the results from the previous step and visualize them.

The details of each step can vary depending on the type of analysis to be performed.

Structural analyses are one of the most common applications of FEM. The term structural refers to many things, from bridges to ships to mechanical components such as pistons. The type of structural analysis that is used for this research is the modal analysis, with which one can calculate natural frequencies and mode shapes of structures. Thermal analyses are used to determine temperature distributions, heat loss or gain, thermal gradients, thermal fluxes, etc. The main types are steady-state analysis, meaning the heat load does not vary in time, and transient analysis, in which the results and loads are time dependent. The latter is used in this research, in the form of a coupled-field analysis, incorporating the modal analysis mentioned above.

3 Literature review

In this section previous research related to the project's themes is shown. Firstly, understanding the background of SHM on which the research question is asked helps with determining what the relevant factors that need to be taken into account are. Then, the effects of temperature on dynamic properties has been thoroughly studied in the past, but still some knowledge gaps can be identified. Lastly, the thesis question is investigated through the means of a FEM, the previously employed methodologies need to be studied in order to facilitate the process of building one's own model.

3.1 Practices of Structural Health Monitoring

Building civil engineering structures like bridges can be a lengthy and costly process and once it is finished the structure still has to be maintained in order to avoid failures and prolong its lifetime. The main goal of SHM is the detection of damage in a structure. Thus, the data from the sensors has to be analyzed to draw conclusion about the integrity of the studied object. This data might come from temperature, acceleration, strain or load sensors. For the purposes of this project, the damage detection method which is discussed is the vibration based one.

One factor which influences the dynamics of a structure is its stiffness. The introduction of damage leads to a decrease in structural stiffness, thus the frequency also undergoes abnormal reductions (Magalhães, Cunha, and Caetano 2012). This is the principle of vibration based damage detection. Meaningful features have to be extracted from the data, ones which give insight into structural integrity, but this can become a very complicated task with the introduction of environmental excitations which introduce noise in the data (Peeters, Maeck, and Roeck 2001; Deraemaeker et al. 2008). There are multiple methods of analyzing sensor data in hopes of detecting anomalies. Sohn (2006) describes a number of such methods: regression analysis, subspace based identification, novelty detection, singular value decomposition, auto-associative neural network. Even though the details of these methods are different, they all require data of the studied object under varying climate as a reference point. This goes to show that the relationship between environment and dynamic properties has to be understood. One of the main influences appears to be temperature (Fritzen 2005), as is demonstrated in many studies.

3.2 Effects of temperature on dynamics

One of the main areas of interest when it comes to temperature variations are long-span bridges, with literature agreeing on the frequency changes in relation to temperature

(G.-D. Zhou and Yi 2014). Temperature is theorized to be the main factor that can influence dynamic changes in structures (La Mazza et al. 2022). These changes do not only pose a problem for data acquisition and analysis, large deviations might also become a safety risk (Cao et al. 2010). When plotting the displacement of a bridge, it is shown to follow the diurnal temperature cycles very closely, while the effects of the traffic loads were much less noticeable, to the point where it could be considered as "noise" on top of the thermal response (Kromanis and Kripakaran 2016).

Figure 4 shows the results of the Tsing Ma Bridge case study which used sensors along the cable bridge to measure temperature (which is considered to be the average through the cross-section weighed by the area around the sensor) and frequency. The inverse relationship as shown in the graphs has been found by many other independent studies, both with the use of physical experiments and computer models (Liu, Z. Chen, and T. Zhou 2012; Xia, Xu, et al. 2011; Xia, B. Chen, et al. 2012; G.-D. Zhou and Yi 2014).

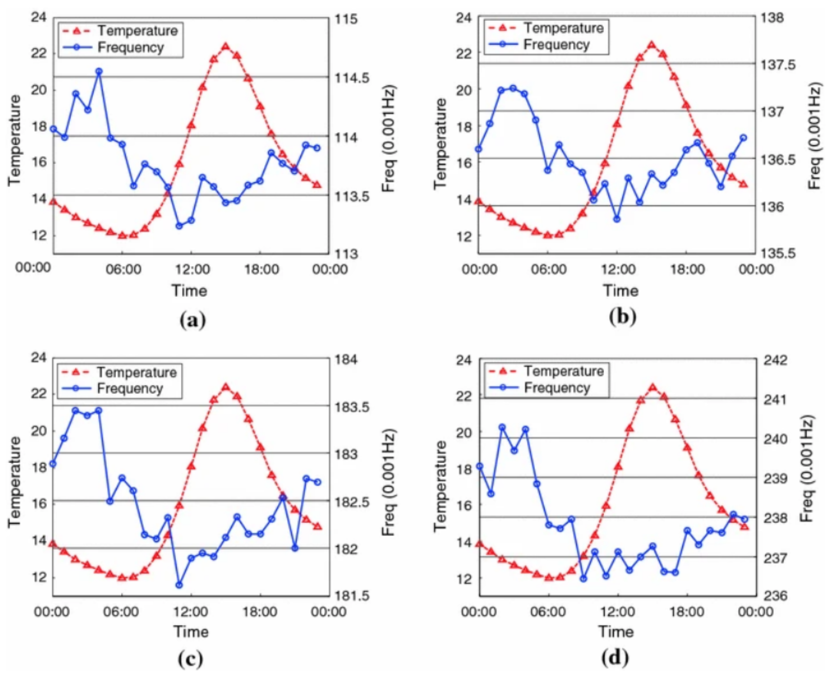


Figure 4: Variations in frequencies with respect to the temperature of the Tsing Ma Bridge on 17 January 2005 (Xia, B. Chen, et al. 2012)

The inverse relation between temperature and frequency does not always hold true, depending on the mode and structure studied. Venglár and Lamperová (2021) shows that the frequency of the first lateral mode of a steel truss bridge increases in relation to the ambient air temperature. Meanwhile the other modes show an inverse relationship. Also, the second structure they studied, yields the same results for the first torsional mode, the frequency goes up with temperature.

One aspect which is also discussed is the problem of temperature distributions and how considering only surface and ambient temperatures leads to erroneous results. A time lag of about 3h has been noticed between the ambient temperature and frequency change, implying that heat has to reach a certain depth before variations can be measured. There is evidence that mean deck temperature is not correlated to changes in frequency, but when taking into account cross-sectional distributions, the tie is more evident (Xia, B. Chen, et al. 2012).

Liu, Z. Chen, and T. Zhou (2012) made an analysis of a H-beam made out of steel and modeled the effect of the sun on its dynamics by utilizing both a computer model and a physical experiment. The results showed a strong correlation between temperature, frequency and damping ratio, but no definitive impact on mode shape. These results are not necessarily in line with those from other studies (G.-D. Zhou and Yi 2014), but it goes to say that the quantification of the effects of temperature on dynamic properties are not very consistent between studies.

The importance of temperature in the dynamic analysis of structures might also be dependent on the season, studies showing that variations of frequency are different in winter and summer, mainly attributed to the fact that sub-freezing temperature affect frequencies differently. A variation of 12% of the first mode and 20% of the second mode was found for a single span railway bridge when temperatures dropped bellow 0°C (Gonzales, Ülker-Kaustell, and Karoumi 2013). While the change in frequency due to material stiffness reduction (damage) are much lower in magnitude, ranging from 3 to 8% (Alampalli 1998).

But temperature is not the effect that causes the changes in frequencies, but rather it causes the elastic properties to vary (Bahr et al. 2013). In general, functions which describe how the modulus of elasticity is influenced by the temperature have been found, one of the most used one being the Wachtman equation: $E = E_0 - B_1 T e^{(\frac{-T_0}{T})}$ (Wachtman et al. 1961). There is no clear equation that can be applied in all situations, as the relationship between Young's Modulus and temperature differs from material to material, so mostly empirical data is used when defining a varying E. As an example, figure 5 showcases different data sets for the E of stainless steel depending on temperature. For the purposes of this thesis, E will be defined using empirical data, by defining its value at certain temperatures.

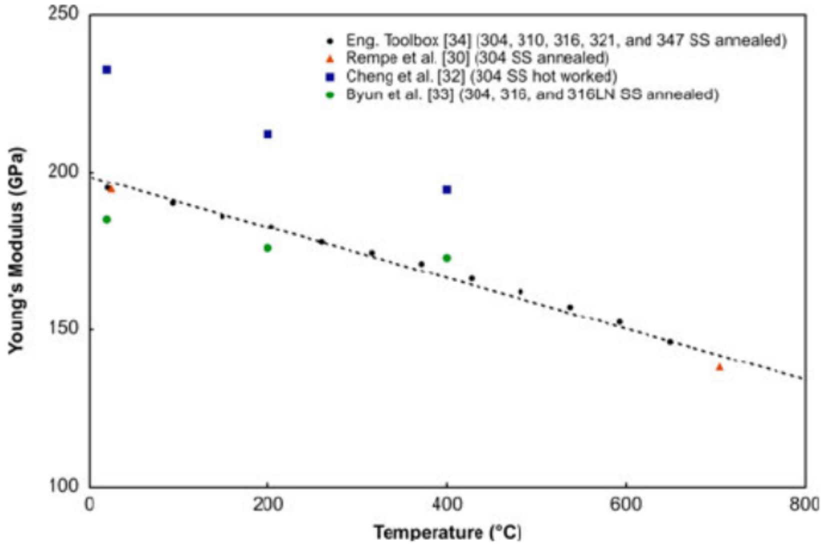


Figure 5: Young's modulus of steel as a function of temperature (Kim et al. 2012)

3.3 Finite Element Analysis methods

Engineers employ virtual models to theoretically study the behavior of objects in certain scenarios. In the context of this paper, the virtual model will showcase the thermal-dynamic relationship.

Xia, Xu, et al. (2011) performed an analysis on a concrete slab by making both a physical and an Ansys model. They have studied the effects of solar radiation on the dynamic properties of the slab. The FEM is subject to a multi-field analysis. It was performed using the decoupled method. This implies that the influence is only one way, the results from the thermal analysis influencing the ones from the modal analysis. The geometry of the model is updated to encompass the deformation due to temperature distributions.

Given that the studied object is a slab, they chose to apply the heat load in the form of surface radiation, changing the intensity with each time-step (1 hour). Thus, they ignored the horizontal heat gradient and took into account only the vertical heat gradient. Using this approach did yield low errors between the measured and simulated temperature values.

3.4 Conclusion

One mode of a structure is described by its frequency, shape and damping ratio. As is stated above, even though the frequency is consistently found to change due to temperature fluctuations, the shape and damping ratio do not show a definitive connection (G.-D. Zhou and Yi 2014). As such, these 2 parameters are not included in this thesis. Studies do show a clear correlation between temperature and the change in modal frequency of structures and quantifying the change allows for the efficient detection of damage. When this relation is described, different definitions for the temperatures are used. In some cases it refers to the surface temperature of the structure, while in others it is an internal temperature, weighed by the area surrounding a sensor. This leads to discrepancies when quantifying the modal changes compared to temperature. Since the thesis aims to quantify the errors which occur due to the assumptions of uniform temperature distribution compared to non-uniform distribution, it should give insight into what is an appropriate definition of temperature when describing modal changes.

The modal frequencies vary to different extents depending on the season. During winter, the modal frequencies show less variation than in summer. This might be due to the lesser effect of sun radiation during the winter months. So, the data used for this thesis are extracted for a winter and a spring day, to cover a wide range of temperatures. But, given that this study is done in the Netherlands, temperatures do not usually drop bellow 0°C, so the bellow freezing scenario is not explored. Rather, what is explored is days in which the sun irradiance has a high variance, allowing for more complex heat distributions throughout the girder, rather than choosing a day with low sun exposures, which would make the heat gradient less noticeable.

In conclusion, the main research gap that this thesis is tackling is the quantification of the effects of temperature distributions on modal frequencies. Since it is well established that temperatures do affect the vibration parameters of structures, for SHM purposes, it is important to know how detailed the temperature distributions have to be defined to ensure that damage can be detected efficiently. Research is mostly focused on just the temperature-frequency relation, rather than quantifying how certain assumptions affect it.

4 Methodology

This paragraph describes the general methodology of the project, starting with the building of the model and then how the data extracted from the model is interpreted. Figure 6 shows the main tasks of the thesis process.

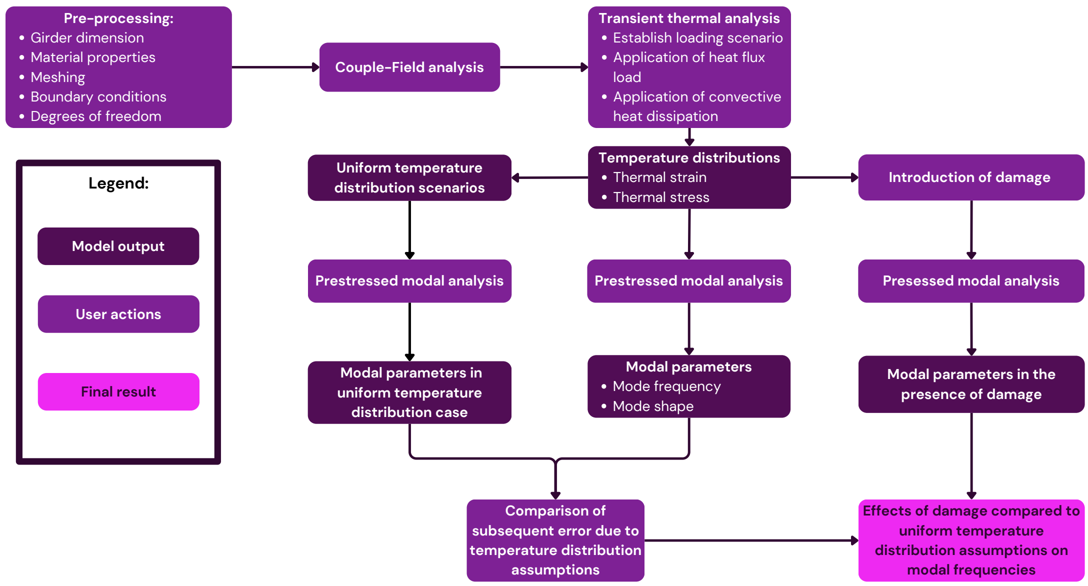


Figure 6: General methodology

A FEM of a girder is subjected to a decoupled thermal-structural analysis. The results of the transient thermal analysis affect the results of the modal analysis. The girder's modal frequencies are studied in three states:

- Reference state - the girder is subjected to a heat load which produces a certain heat gradient across its volume, which is assumed to be a realistic temperature distribution;
- Damaged state - same as in the reference state, but damage is introduced in the form of material loss at a point in the structure;
- Uniform scenario - the girder is assumed to have the same temperature across its volume, equal to the ambient temperature.

There are certain steps that need to be taken in order to perform an analysis. Starting with the pre-processor step, the dimensions of the studied object have to be defined. Then the object is meshed according to the desired element type. There are constraints regarding how fine the mesh is, since smaller elements lead to a higher processing time. Each element has to be attributed a material, properties of which can be either user defined or taken from an existing library. Depending on the type of analysis performed, the needed properties can differ. For the structural-thermal analysis, the user must specify: density, Young's Modulus, coefficient of thermal expansion, specific heat and thermal conductivity. The units must be assigned consistently, in a user defined system. Final part of the pre-processor is the constraining of the studied object. For the structural analysis the support type has to be determined and for the thermal analysis the environment in which the object is in.

The next step is the solution stage. For the transient thermal analysis it is important that the initial temperature of the object is within the scope of the analysis, otherwise the application of a heat load might lead to non-realistic results. Transient implies that the state of the system is time dependent. This type of analysis is used since the girder is subject to a heat load that varies in time and space. The length, number and load value at the end of each time step is determined. To model the sun's effect, heat flux is applied as a surface load on one of the object's faces, while the other ones are subject to convection, since the two cannot be applied on the same area simultaneously. The convection degree of freedom allows the girder to dissipate heat to its environment. Internal conduction throughout the girder's volume is applied automatically, in accordance with the user specified material properties. The thermal effect of the sun on a given object has many components, as can be seen in Figure 7. For this thesis, the total irradiance is considered to be the sum of the direct, diffuse and reflected irradiance, without taking into account the interaction with the ground. Convection requires information on the ambient temperature and the convection coefficient. For the structural analysis, the user must state the desired number of modes the software computes. The modal analysis is performed after each of the time steps of the transient-thermal analysis, to get a more comprehensive view of the effects of heat gradients on modal parameters throughout a day.

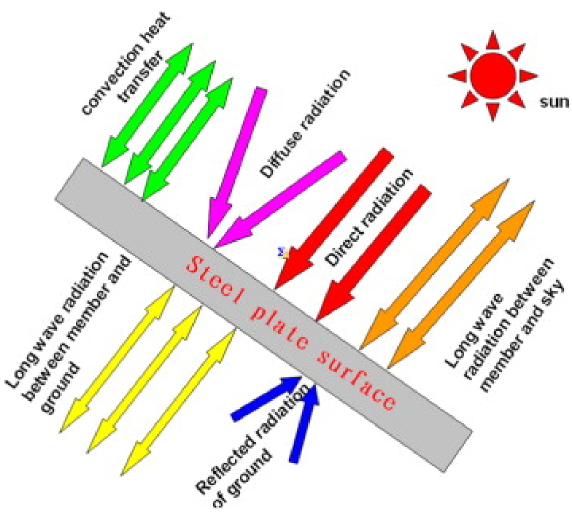


Figure 7: Sun radiation impact components (Liu, Z. Chen, and T. Zhou 2012)

The last stage is the post-process, in which the user can extract and visualize the solutions from the previous stage. The frequencies of the first 3 modes are extracted.

In order to simulate the damaged state of the girder, some of its elements are attributed a Young's Modulus of 1 Pa. Similar approaches to simulating damage have been done in the past (Berardengo et al. 2023), but usually the E reduction is carried incrementally. In this project the damage is assumed to be more severe, which would lead to higher frequency variations.

4.1 Data interpretation

The frequencies of the first three modes of the girder in the reference state are compared to those computed for the damaged and uniform state. This is done to quantify the extent to which damage and uniform temperature assumption affect the modal frequencies of a structural element, in the form of relative errors. Finally, the subsequent relative errors from the damaged and uniform state are compared, to see which has a more pronounced effect on modal frequencies. Equations 9 to 11 are used for quantifying the errors.

$$\epsilon_u = \frac{|\omega_u - \omega_r|}{\omega_r} * 100 \tag{9}$$

$$\epsilon_d = \frac{|\omega_d - \omega_r|}{\omega_r} * 100 \tag{10}$$

$$\Delta\epsilon = \epsilon_d - \epsilon_u \tag{11}$$

- ϵ_u [%] - relative error due to the uniform state assumption
- ϵ_d [%] - relative error due to the damaged state assumption
- $\Delta\epsilon$ [%] - difference between relative error in the damage state and uniform state
- ω_r [Hz] - frequency of a mode at a certain time step in the reference state
- ω_u [Hz] - frequency of a mode at a certain time step in the uniform state
- ω_d [Hz] - frequency of a mode at a certain time step in the damaged state

5 Finite Element Model

The case study is a 3m HE 200B steel girder, with material properties as described in Table 1. The dimensions of the beam in mm are shown in Figure 8. It is meshed using the tetrahedral element SOLID225, which has both structural and thermal DOF, with an edge of 10mm.

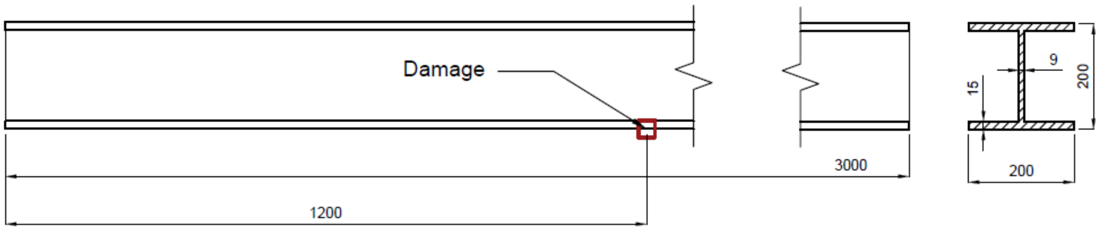


Figure 8: Girder details (dimensions in mm)

Table 1: Material Properties for structural steel

Material Property	**Steel**
Density - ρ	7850 $\frac{kg}{m^3}$
Young's modulus - E	210*10^9 Pa
Coefficient of linear	
thermal expansion - α	12*10^{-6} $\frac{1}{K}$
Specific heat - C	490 $\frac{J}{kgK}$
Thermal conductivity - k	54 $\frac{W}{mK}$

For the transient thermal analysis data regarding the ambient temperature and sun irradiance in intervals of 1 h is extracted from The European Commission Photovoltaic Geographical Information System (2024), for two days: May 25th and February 15th. They have the highest variance in sun irradiance intensity in 24 h for their respective seasons. The location from where the data originated from is on the University of Twente campus, near the Abraham Ledeboer Park. The ambient temperature and heat flux (sun irradiance) values are shown in Figure 9. For the two loading scenarios, winter and spring, the girder is assumed to have a different position relative to the sun, as is shown in Figure 10. This is done to diversify the temperature distributions between the loading scenarios, which could give more insight into their effects on modal frequencies, rather than assuming the same position for both of the chosen days.

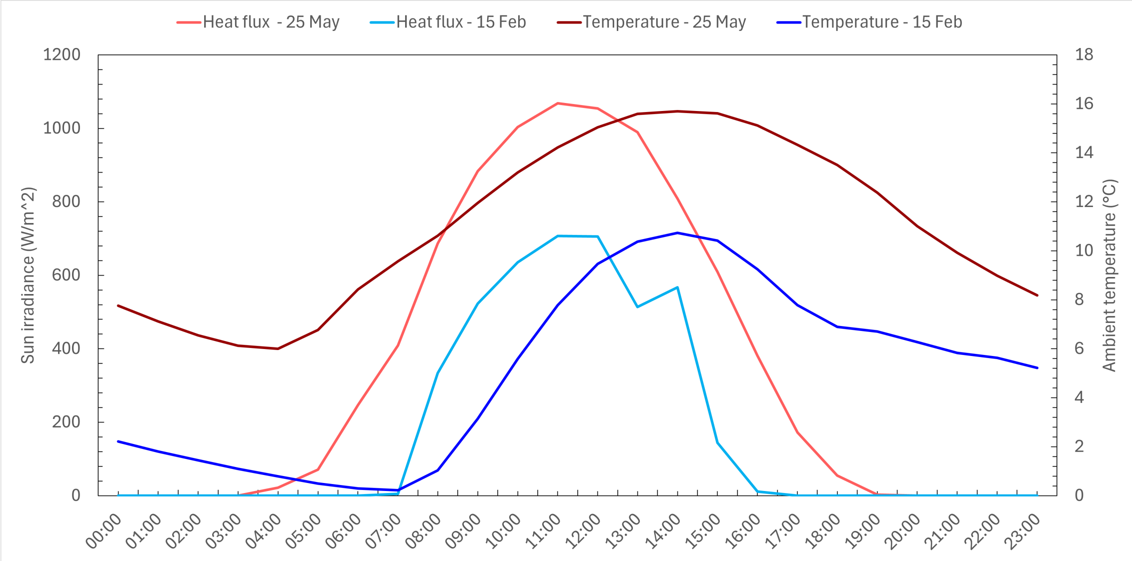


Figure 9: Ambient temperature and sun irradiance for the two loading scenarios

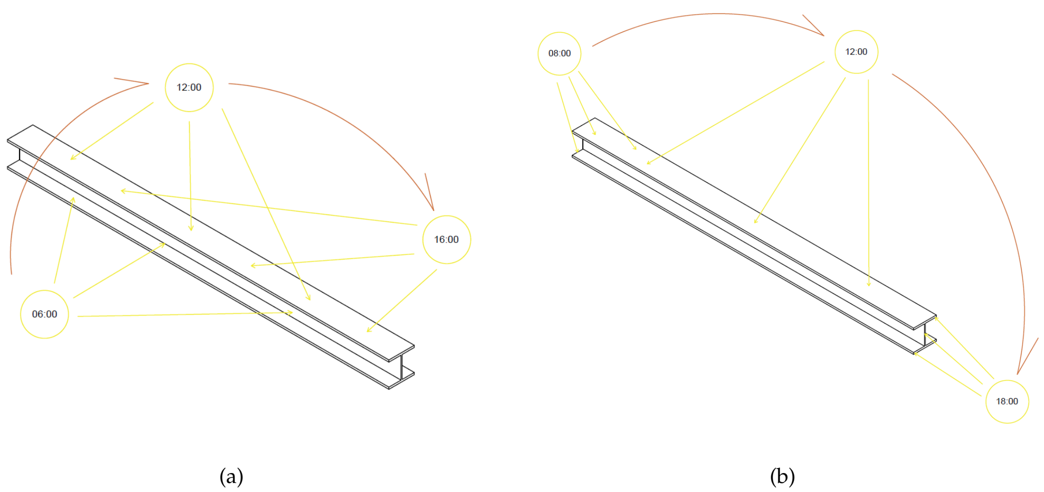
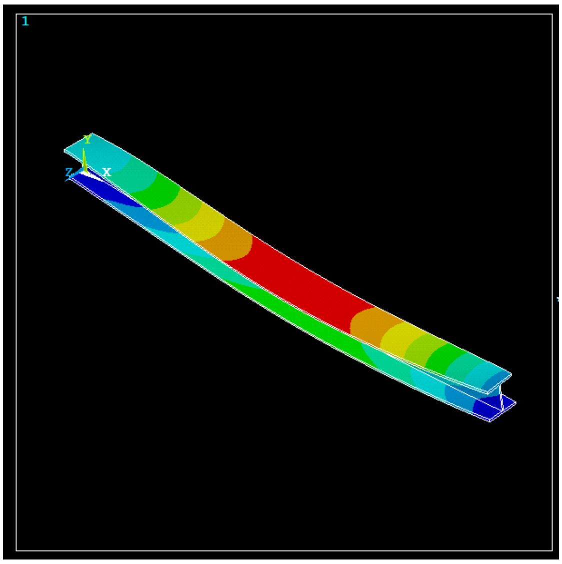


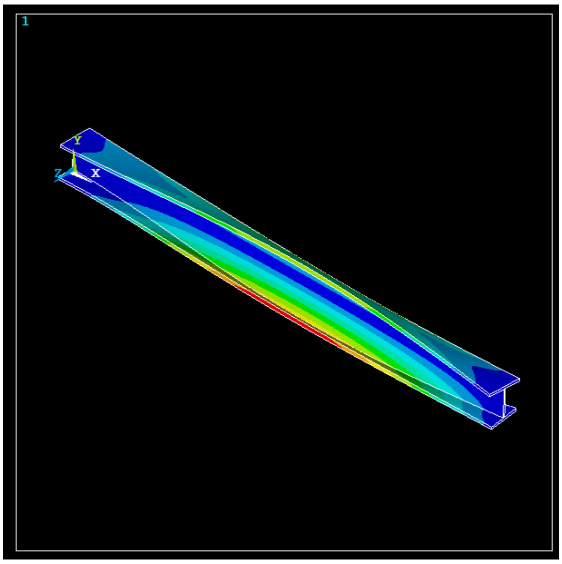
Figure 10: Sun path for (a) Winter day and (b) Spring day

The modal analysis is performed at the end of each time step (1 h) of the transient thermal analysis and studies the frequency. The first mode is lateral ($\approx 2.03Hz$), second is torsional ($\approx 2.45Hz$) and third is vertical ($\approx 3.38Hz$) . They are represented in Figure 11. In order to capture the temperature effect on the modal parameters, the thermal strain and stress calculated from the transient analysis is saved and applied as input for the modal analysis, thus turning it into a pre-stressed modal analysis.

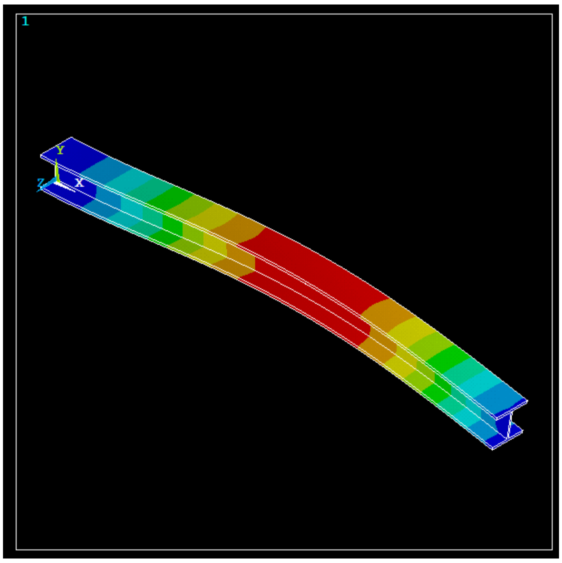
Lastly, damage is introduced at the bottom of the girder, at 1.2m along the X-axis (Figure 8). Due to the element size used for the meshing of the girder, the crack has a width of 10 mm. This will serve as a comparison between the effects of the uniform state and damaged state on modal parameters. The modal frequencies are studied again per each time step of the thermal transient analysis in the reference state, but in the presence of damage.



(a)



(b)



(c)

Figure 11: Modal shapes (a) Mode 1; (b) Mode 2; (c) Mode 3

5.1 Results

In this section, the results of the coupled-field analysis are discussed. Starting with the temperature distribution due to the two thermal loading scenarios, followed by the modal frequencies in relation to the uniform and damaged state.

5.1.1 Winter loading scenario

In the winter day, February 15th, the temperature in the girder ranges from 0.28°C to 27.43°C throughout the 24 h period. The maximum temperature difference, defined as ΔT=T_{max}-T_{min}, is 19.32°C, occurring at 10:00. Figure 12 shows how the temperature is distributed in the girder at this time. This suggests that ϵ_t should also reach its peak at this time.

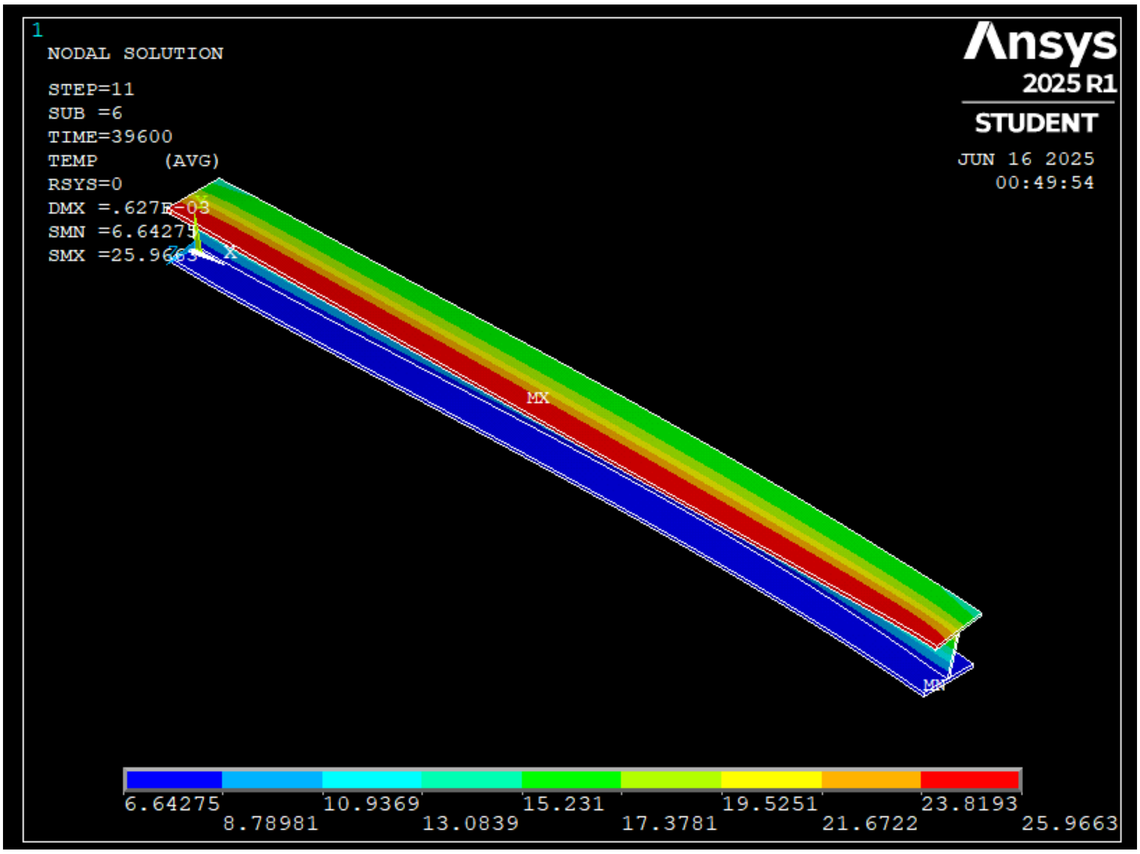
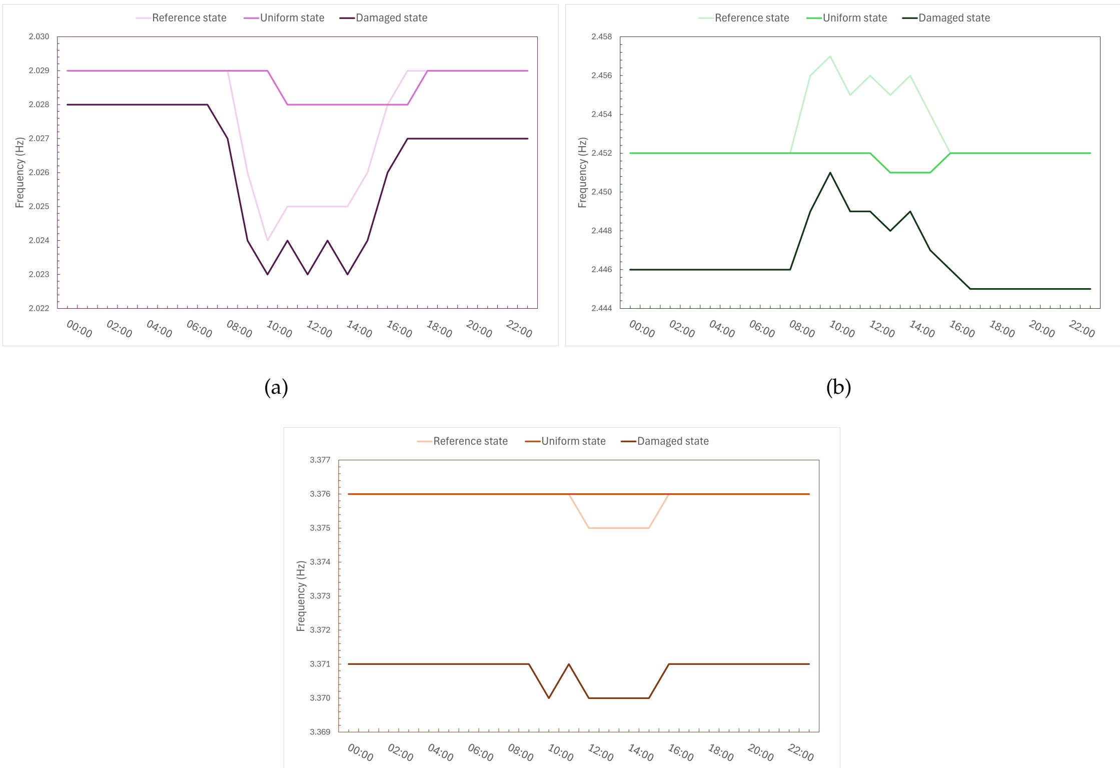


Figure 12: Temperature distribution at 10:00 - winter day

The resulting frequencies from the pre-stressed modal analysis of all the states are represented in Figure 13. The frequencies in the damaged state are lower than those in the reference state, which is consistent with previous studies (G.-D. Zhou and Yi 2014; Alampalli 1998). Furthermore, mode 1 and 3 do experience a drop in frequencies as the system's temperature rises, which is in line with other studies (Xia, B. Chen, et al. 2012), but mode 2 does not follow the same inverse relationship, which can be related to its displacement pattern, it being a torsional mode (Venglár and Lamperová 2021). Rather, the frequencies rise with temperature. In the uniform state, the effects of temperature are less noticeable than in the reference state. The frequencies still vary throughout the day, but to a much lesser extent.

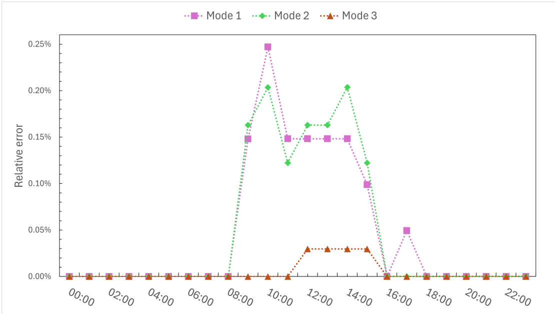


(a) (b) (c)

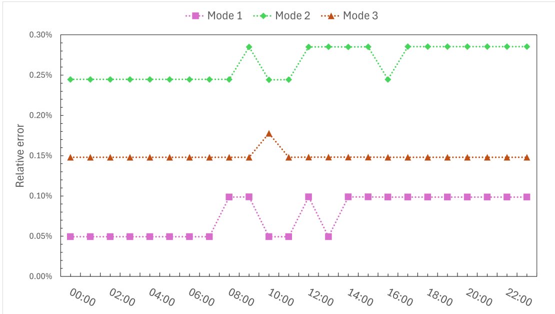
Figure 13: Modal frequencies in all three states - winter day (a) Mode 1; (b) Mode 2; (c) Mode 3

Figure 14 shows the relative errors caused by the uniform state, damaged state and the difference between the two. The uniform state introduces substantial errors in the computing of modal frequencies for mode 1 and 2. Meanwhile, mode 3 remains mostly unaffected by the temperature assumption, apart from the 4 time steps from 12:00 to 15:00, even so the error is minimal at only 0.03%. The highest ϵ_u for mode 1 and 2 is observed at the 10:00 time step, being equal to 0.25% and 0.20%, respectively. In the damaged state, mode 1 experiences the lowest frequency shift, while mode 2 has the highest resulting relative error.

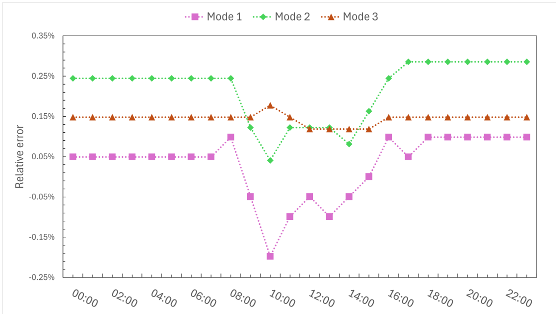
The comparison between the two states results in different conclusions based on the studied mode. For mode 1, the errors due to the introduction of damage are less pronounced than those of the temperature assumption, while for mode 2 and 3 the opposite is true. Furthermore, because ϵ_u follows almost the same pattern as the ambient temperature, when quantifying whether the effects of damage or temperature assumption are more evident, the same pattern is observed. This would imply that, in order to include/exclude the thermal effects on dynamic properties, the temperature range has to be considered.



(a)



(b)



(c)

Figure 14: Relative errors - winter day (a) ϵ_u; (b) ϵ_d; (c) $\Delta\epsilon$

5.1.2 Spring loading scenario

In the spring day scenario the temperature in the girder ranges from 6.03°C to 33.89°C throughout the 24h. The highest ΔT recorded at a point in time in the girder is 18.47°C, at 11:00 (Figure 15), which is lower than in the winter day scenario. This would imply that the highest ϵ_t should be at 11:00.

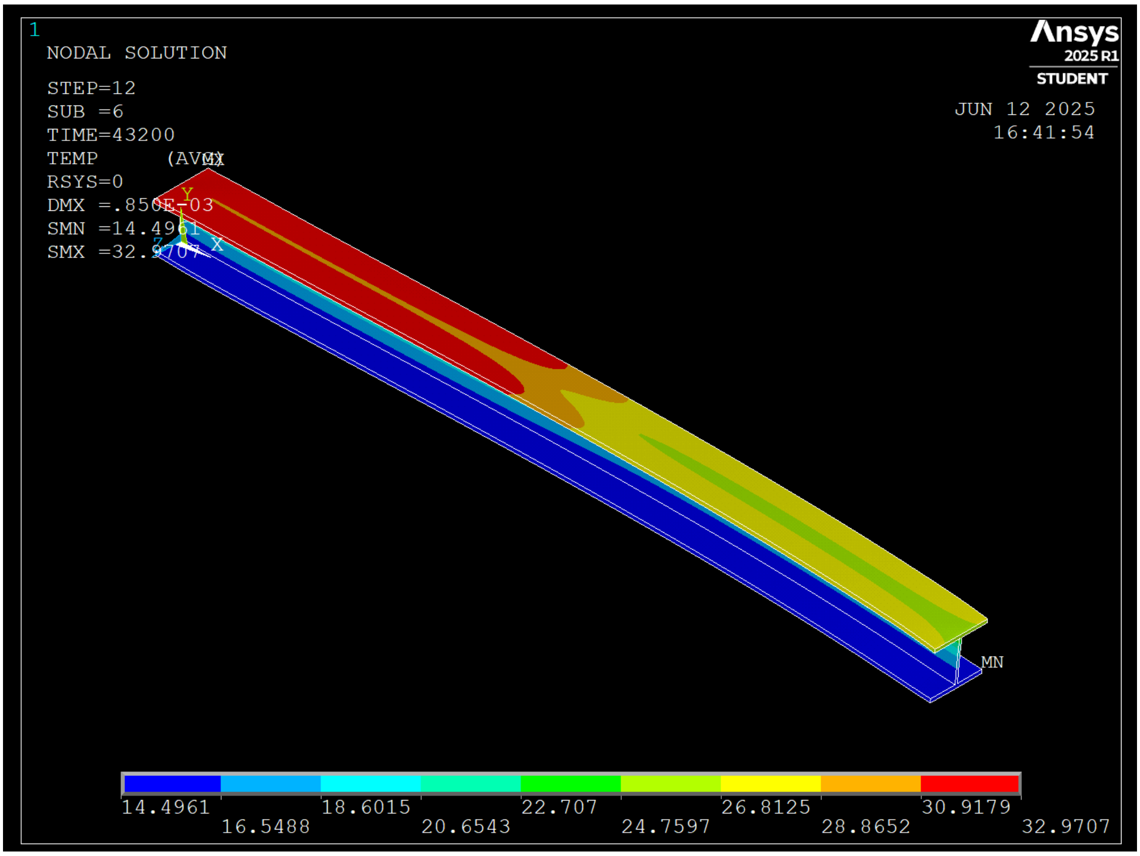
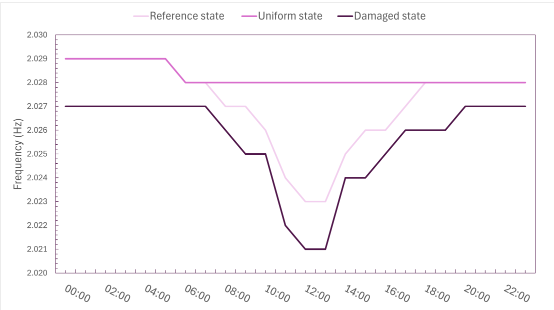
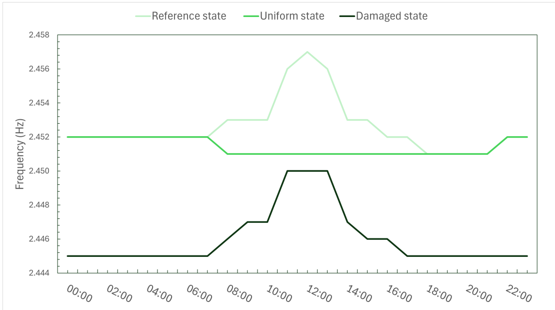


Figure 15: Temperature distribution at 11:00 - spring day

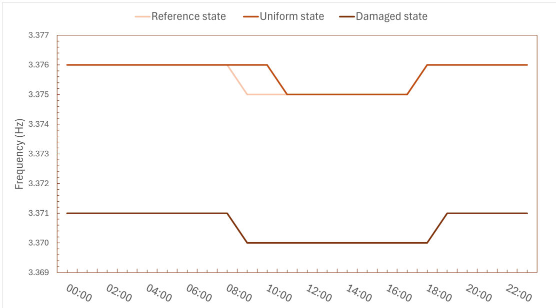
The frequencies of the modes in all three states are shown in Figure 16. Mode 2 exhibits the same behavior as in the winter day analysis. But, for both of the thermal loading scenarios, the frequencies in the uniform state do display the expected inverse relation to temperature. Furthermore, it appears that even if the frequencies do vary in the uniform state, the variation is not as extreme as in the reference state. Since the effects of sun irradiation are not included in the uniform state, the girder's temperatures do not rise as much, thus frequencies do not experience the same drop in value.



(a)



(b)

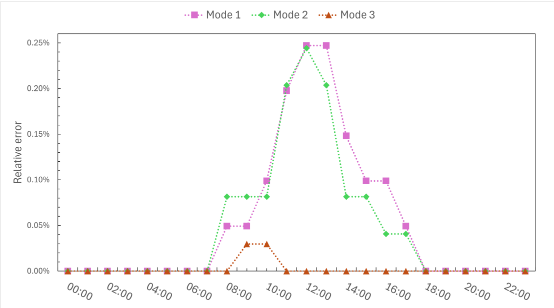


(c)

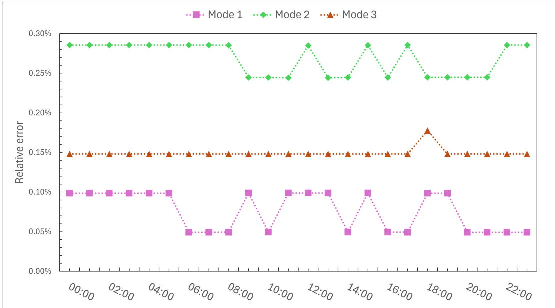
Figure 16: Modal frequencies in all three states - spring day (a) Mode 1; (b) Mode 2; (c) Mode 3

As is the case in the winter day, mode 3 yields almost no error due to the uniform state assumption, besides at 09:00 and 10:00, when the error is 0.03%. The highest relative errors due to the temperature assumption for mode 1 and 2 is 0.25% and 0.24%, respectively, at 12:00, even though the highest ΔT is observed at 11:00. The ϵ_d does not vary too much throughout the day, each mode oscillating between one of two relative errors, without any recognizable pattern. $\Delta\epsilon$ has the same distribution throughout the day as the ambient temperature, and, again, mode 1 is the only one for which the effects of damage are less pronounced than those of temperature assumption.

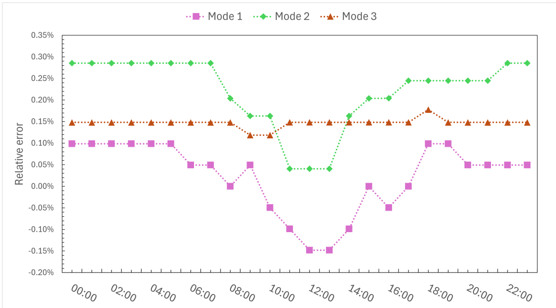
In general, the observations from the winter and spring thermal loading scenarios are the same, the ϵ_u following the same distribution as the ambient temperature. This would imply that as temperature rises, the effects of damage become less evident, being surpassed by the heat gradient.



(a)



(b)



(c)

Figure 17: Relative errors - spring day (a) ϵ_u; (b) ϵ_d; (c) $\Delta\epsilon$

5.2 Discussion

The results of the analysis showcase the importance of temperature distribution assumptions in the accuracy of modal frequency computing. Although the uniform distribution state introduces errors, they follow a consistent pattern across both the thermal loading scenarios: winter and spring. This suggests that a mathematical model can be devised to compensate for the effects of thermal distribution assumptions, in which the function $\epsilon_\omega(T)$ would describe the variation of the frequency in relation to the ambient temperature. Nonetheless, the studied object of this project is an idealized and simplistic model. As such, future research would need to first expand upon the findings by applying the same methodology to more complex structures such as composite bridges, or even a non-uniform cross-section such as reinforced concrete. In these cases, both thermal gradients and dynamic responses may exhibit more complex responses than in the case study presented here. For example, the steel girder would deform more than the wooden deck it supports, which leads to the frequencies of the bridge to vary in a less predictable way than is presented in this research.

Another insight is given by the stability of mode 3 against the assumptions of thermal uniformity. Mode 3 consistently maintained the same frequencies as in the reference scenario, unlike mode 1 and 2 which experienced significant modal variations. This suggests that mode 3 can be used as a thermally-independent damage detection parameter. This behavior can be explained by the nature of the mode. The girder that was studied has a HE profile, which can withstand high vertical loads without significant bending. Given that mode 3 is characterized by vertical displacement, the resulting thermal strains can have less of an impact on the way it bends, thus frequencies are less susceptible to variations. Even when observing the frequency shifts throughout the 24 h of the two thermal loading scenarios, it becomes apparent that they are of a much lower scale compared to mode 1 and 2. If this robustness is incorporated in SHM practices, it may increase the reliability of damage detection methods.

The torsional mode of the girder experienced a rise in frequency due to higher temperature. Given that the introduction of damage lead to a decrease in natural frequency, the temperature effect can mask the one of damage. If it is assumed that the temperature of the girder is the same as the ambient air, the computed frequencies do not rise, thus allowing for the subsequent frequency drop due to damage to remain undetected, compared to when the full thermal gradient is taken into consideration. On the other hand, since the uniform state assumption leads to the frequencies of mode 1 and 3 to be computed as higher than their actual value, the introduction of damage is easier to detect, but false positives are more likely. As such, the behavior of all three modes needs to be evaluated in parallel, in order to avoid unnecessary interventions or failure to detect damage.

In conclusion, even if the uniform distribution assumption does introduce errors in modal frequency calculation, their consistency can be an opportunity to incorporate correction methods in the data processing steps of SHM. Again, mode 3 can improve the reliability of damage detection due to its robustness against temperature gradient variations. Although the studied system lacks the complexity of those in practical applications, this study can be viewed as a first step in understanding how certain temperature distribution assumptions affect the reliability of vibration based SHM. Further studies should build on this model and adapt it so it can better represent real-life structures.

6 Conclusion

This thesis presents an investigation into the influence of temperature distribution assumptions and structural damage on modal frequencies of a simply supported steel girder. The structural element is subjected to two representative thermal loading scenarios: a winter day and a spring day. The study aimed to quantify to what extent idealized temperature distributions affect the accuracy of modal frequency computation. The analysis focused on the natural frequencies of the first three modes of the girder. Mode 1 is a lateral mode with frequencies around 2.03 Hz. Mode 2 is exhibits torsional displacement at around 2.45 Hz. Mode 3 is oscillates vertically at around 3.45 Hz. The following conclusions could be made:

- The heat gradients that resulted from the transient thermal analysis introduced significant thermal strains in the girder, which lead to variations in frequencies throughout the 24 h periods of the two studied scenarios;
- The assumption of uniform thermal distribution equal to the ambient temperature yields significant errors for mode 1 and 2 of the girder, but they are consistent between the two thermal loading scenarios;
- The resulting errors from the uniform temperature state have the same distribution as the ambient temperature;
- Mode 3 seems to remain minimally affected by temperature variations, in both the uniform and non-uniform temperature distribution states, which affirms its role as a temperature-independent damage detection parameter;
- The effect of damage introduction is pronounced for mode 2 and 3, while mode 1 reacts more to thermal changes in the structure, thus the uniform state yields to bigger errors, making it an inappropriate assumption to make;
- The frequencies of mode 1 and 3 show an inverse relation to temperature, while the frequency of mode 2 rises with an increase in heat.

As such, the findings of this thesis do indicate that the assumption of uniform temperature distribution along the length of an element is acceptable depending on the studied mode. However, this assumption must be properly integrated in data processing, compensating for the known error patterns that arise. Failure to do so may result in false positives or negatives, especially in cases where there exist large diurnal or seasonal temperature fluctuations. Even if uniform temperature assumptions simplify the data processing step of SHM and reduce the number of sensors needed in a structure, it cannot be blindly trusted. The limitations that come as a result have to be accounted for in the interpretation of acceleration data.

This study also tackled a very simplistic model, thus future studies should aim to extend the methodology to more realistic structures. This would allow for the results to be generalized for a wide range of applications. Furthermore, regression models could be devised in order to incorporate the effects of the uniform temperature gradient assumption in the data processing step of SHM, thus reducing the computational power needed.

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