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Experimental study on the influence of environmental variables on the dynamic monitoring of full-scale structures

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Abstract. As the field of Structural Health Monitoring (SHM) continues to advance, the influence of environmental variables on the dynamic response of structures has become increasingly significant. Understanding the impact of environmental factors, particularly temperature, on the dynamic behaviour of civil structures is crucial in Vibration-Based Structural Health Monitoring (VB-SHM). In fact, in most cases the structural diagnostic features are influenced by external environment which causes fluctuations that can be confused with the appearance of damage, or in the worst case, hide it. Therefore, accurate diagnostic techniques are essential to distinguish between normal environmental variations and changes due to structural damage, thereby reducing the occurrence of false positives and false negatives, which can result in significant waste of time and resources. Environmental factors can affect both the mass and the stiffness of the system; precipitations such as snow or rain could be seen as a mass addition to the system, which could last for days, until the liquid stored in the cavities or porosities of the materials dries completely. While variations in temperature could affect stiffness, for example due to the effect of freezing which tends to stiffen the body. Predicting the effect that these factors have on the structure is a key aspect and it is not trivial.
The existing literature identifies various relationships between environmental variables and the dynamic behaviour of structures, with these relationships often varying according to the type of structure. These trends can certainly depend on the structural scheme and the material, but also on a series of other aspects.
This paper shows some relationships experimentally found on very simple systems characterized by different materials, in order to better understand these findings respect to data from real structures to identify analogies. The study highlights the importance of accounting for environmental variations to improve the accuracy and effectiveness of SHM in preserving structural integrity.

Keywords: Structural Health Monitoring, Natural frequencies, Environmental and Operational Variations, Temperature, Masonry.

1 Introduction

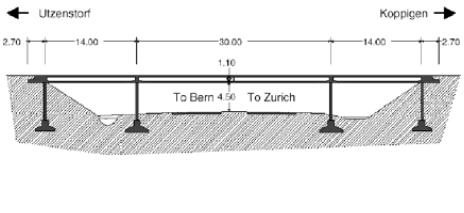
Structural Health Monitoring (SHM) has become an essential tool for ensuring the safety and durability of civil structures, particularly given the growing complexity of modern constructions. One of the most significant challenges in this field is the ability to accurately assess structural integrity under variable environmental conditions. Factors such as temperature fluctuations, precipitation, and humidity can significantly influence structural behaviour, thereby complicating the interpretation of monitoring data. These variations can imitate damage signals or, conversely, hide their presence, undermining the effectiveness of Vibration-Based Structural Health Monitoring (VB-SHM). The impact of environmental factors on structural behaviour is particularly evident in parameters such as mass and stiffness. For instance, precipitation can act as a temporary mass load, while temperature variations can alter stiffness, as in the case of freezing, which temporarily stiffens the structure. Although these effects are often reversible, they can nonetheless introduce noise or distortions into diagnostic processes, leading to delays in interventions or wasted resources. The influence of environmental factors on dynamic structural response underscores the importance of accurate diagnostics. In particular, the reversible effects caused by environmental variations can result in either false positives, leading to unnecessary interventions and resource wastage, or false negatives, which delay critical maintenance and, in extreme cases, compromise structural integrity and public safety. Although the relationship between environmental factors and structural response has been explored extensively in the literature. The observed variability highlights the complexity of the phenomenon and emphasizes the need to consider additional factors, such as structural typology, material properties, geometry, boundary conditions, and different ambient variables in the analysis. This study addresses this context by focusing on the relationship between temperature and natural frequencies, with the goal of identifying which factors could influence this interaction. By analysing simple experimental systems made of different materials, this research attempts to provide some results that can guide the interpretation of monitoring data from more complex structures. Ultimately, it aims to improve the reliability and accuracy of SHM techniques, contributing to the field capacity to preserve and protect structures and infrastructures.

2 Effects of environmental variables on structural behaviour

Among the various challenges encountered in SHM, one of the most significant concerns the ability to clearly and accurately recognize hazardous situations indicative of structural damage, which require timely intervention. Civil structures are constantly exposed to weather factors and environmental variations, making the understanding of the relationship between environment and structural behaviour essential for effective monitoring. In this context, when assessing the health conditions of a structure, it is crucial to consider the entire system in which it is embedded, referred to as the environment-soil-structure system [1]. The surrounding environment can directly influence the structure but also indirectly through its impact on the underlying soil, which

subsequently affects the structure itself. This holistic approach is fundamental for a comprehensive understanding of the structural behaviour and for obtaining a global view of the structural health. Environmental factors, in fact, can influence both the mass and the stiffness of the structure, altering diagnostic parameters such as elastic properties and natural frequencies. The external effect on structural behaviour represents a significant obstacle in monitoring, as it may obscure analyses and lead to misinterpretation of collected data, particularly when data-driven methods are employed, thus compromising the accuracy of evaluations. Failing to distinguish between physiological and pathological conditions could compromise the structural integrity, causing irreversible damage. In the most severe cases, it could even endanger human lives, highlighting the critical importance of making this distinction. In this context, two types of errors may arise during monitoring: False Positive Error (FPE) and False Negative Error (FNE). The first one occurs when an environmental effect is incorrectly interpreted as structural damage. This condition may frequently arise if the "healthy" thresholds for the structure are set with a large safety margin. In such cases, each extraordinary climatic event (which may last for several days) triggers a false alarm, leading to the mobilization of a team of technicians to inspect the structure, along with the potential evacuation of personnel. This results in an inefficient, costly, and unnecessarily restrictive monitoring protocol. On the other side, the FNE happens when the presence of damage in the monitoring data is attributed to ambient effects. In the best-case scenario, this simply delays the necessary intervention, although this increases the invasiveness of the damage as it progresses. In more severe cases, the structure could be compromised before the error is identified, eliminating the possibility of intervention and turning monitoring essentially useless. While less frequent than the FPE, this scenario can have dramatic consequences, leading to irreversible losses to built heritage, including the structure itself and any cultural objects it houses, as well as endangering individuals within or around the building. Therefore, it is essential, during SHM process, to accurately distinguish between physiological conditions, where the structural behaviour changes naturally and reversibly in response to environmental variations, and pathological conditions, where the structure may experience irreversible changes. However, predicting the effect of these factors on the structure is not a trivial task and requires the collection of a significant amount of data over an extended period in order to fully explain the structural behaviour in the presence of environmental variations. The literature provides valuable information, particularly for assets monitored continuously or over the long term, as collecting a large volume of data allows for better definition of the existing relationships. For instance, with regard to temperature and modal frequencies, directly proportional relationships have been observed [2–4], bilinear relationships [2,5–7], and inversely proportional ones [8], with the proportionality depending on the considered mode [9]. Furthermore, for the same structure, some modes are closely correlated with thermal conditions, while others appear to be almost entirely uncorrelated [10]. Among the various environmental variables, this study focuses on the relationship between temperature and natural frequencies. The main objective is to identify and recognize the different factors that could influence this relationship, as the analysis of case studies available in the literature seem not to detect a well-defined pattern that would allow for the expecta-

tion of a clear trend. This is because, as mentioned earlier, the factors involved in this phenomenon could be multiple.



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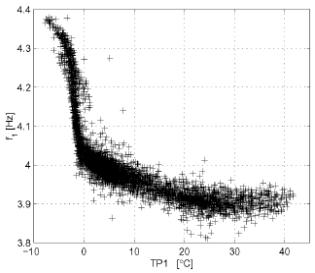

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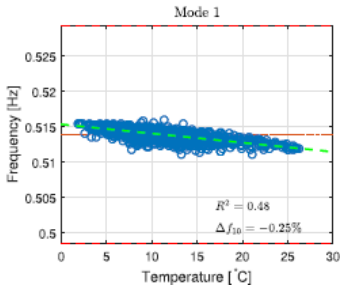
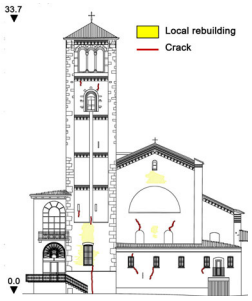
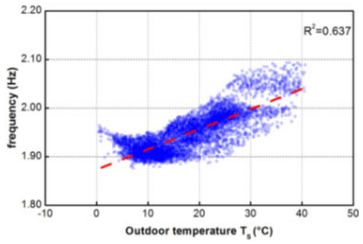


(d)

Fig. 1 Relation between frequencies and temperature for bridges from [5] and [4] : (a) Z24 bridge, (b) frequency-temperature scatter-plot, (c) KW51 steel bridge, and (d) frequency-temperature scatter-plot.

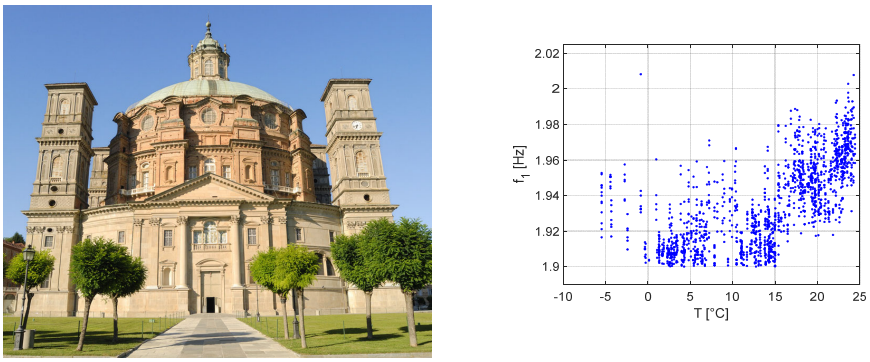


(a)



(b)

Fig. 2. Relation between frequencies and temperature for Architectural Heritage : (a) Bell tower of Santa Maria del Carrobiolo in Monza [10], (b) frequency-temperature scatter-plot.



(a) (b)

Fig. 3. Relation between frequencies and temperature for Architectural Heritage : (a) the Sanctuary of Vicoforte, and (b) frequency-temperature scatter-plot.

3 Experimental methodology

To investigate the relationship between ambient temperature and the natural frequencies of a structural system, a controlled laboratory experiment was conducted. The study aimed to reduce uncertainties related to factors such as structural typology, boundary conditions, material properties, and other environmental variables. To simplify the analysis and isolate the influence of the different factors, it was decided to vary only the material of the structure and the mass, keeping the other parameters constant, in order to assess the effect of temperature on the dynamic behaviour of the system. The experimental setup consisted of a Single-Degree-of-Freedom (SDoF) system (Fig. 4(a)), where a column was fixed at the base using a metallic structure. This structure consisted of two metallic plates: a top "U"-shaped plate (Fig. 4(d)) with a side length of 200 mm, thickness of 3.5 mm, and height of 50 mm and a bottom plate (Fig. 4(e)) with a side length of 300 mm and thickness of 3.5 mm. A cubic hollow metallic profile, with an external side length equal to 50 mm, a thickness of 3.5 mm, and a height of 40 mm, was welded at the centre of both plates (Fig. 4(d-e)), serving as a fixture for the column. A steel cube (Fig. 4(c)), with a side length of 185 mm and a mass of 25 kg, was applied during the experiments. Three different configurations were tested, each corresponding to a different column material:

(I) steel column (Fig. 4(f)) with a hollow cubic profile (external side 45 mm, thickness 1 mm, height 500 mm, density ρ=7850 kg/m³);
(II) concrete column (Fig. 4(g)) (side length 44 mm, height 500 mm, density ρ=1300 kg/m³);
(III) masonry column(Fig. 4(h)) (side length 44 mm, height 250 mm, density ρ=1800 kg/m³).

Thus, based on the information above, the experiment was conducted ensuring that the stiffness, constraints, structural type, and, in part, the geometry remained unchanged. Regarding the geometry, the variation in the height of the columns in the three configurations was a necessary choice to maintain the system stiffness constant. The 25 kg steel cube applied to the system allows the own mass of the columns to be neglected, as it is significantly lower than the mass of the cube itself. The main difference between the three configurations analysed is the density of the materials composing the columns. However, in the frequency calculation, it is not directly the density that affects the results, but rather the overall mass, which includes the density and is the parameter that actually influences the frequency variations. Fig. 4(b) provides a detailed view of configuration (I). For clarity in representation, the steel cube is not shown in the figure.

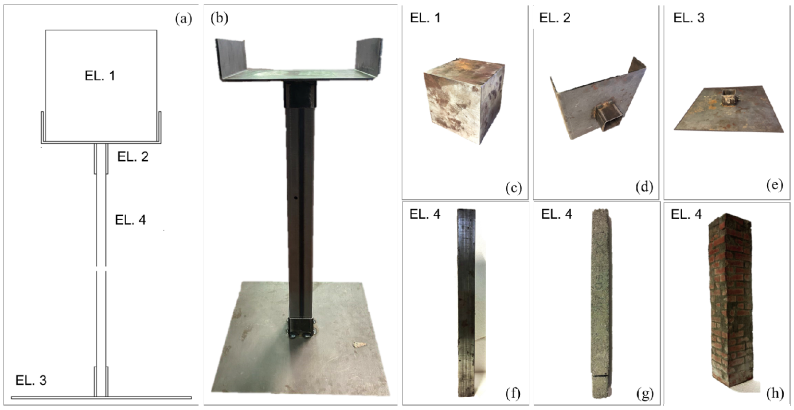


Fig. 4. Experimental setup: (a) Setup design, (b) Iron framework, (c) Steel cube, (d) Upper iron plate, (e) Lower iron plate, (f) Steel column, (g) Concrete column, and (h) Masonry column.

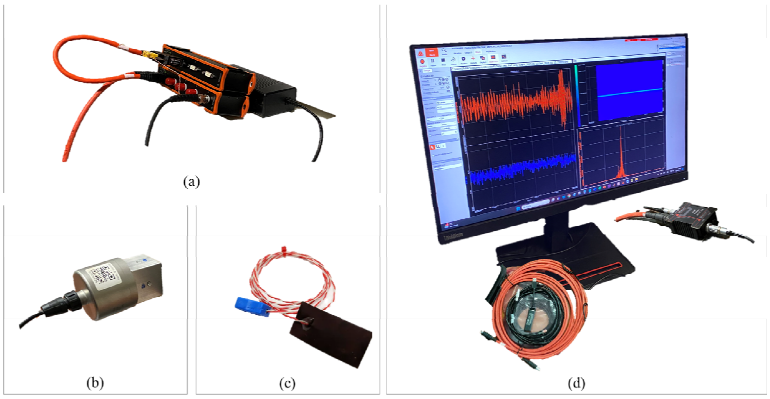


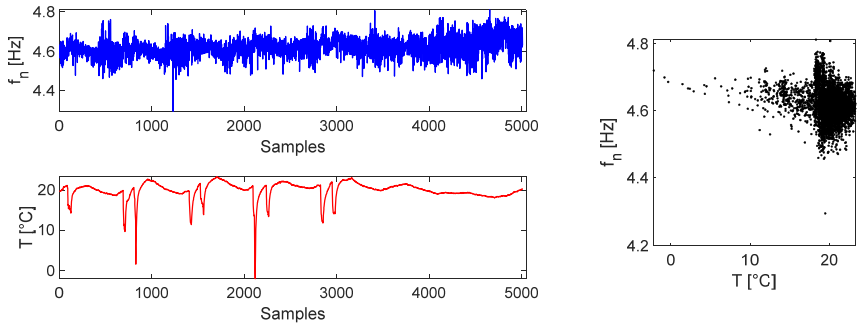
Fig. 5. Sensors and acquisition system: (a) Static (up) and dynamic (bottom) acquisition unit ,(b) Accelerometer, (c) Thermometer, and (d) Pc and cables

To monitor the system response, a data acquisition system was employed, consisting of a static 3-channel acquisition unit (Fig. 5(a)) (KRYPTON-3xSTG) and a dynamic 4-channel acquisition unit (Fig. 5(a)) (KRYPTON 4xACC) that are synchronized through the orange cable that connects them to each other. A type K thermometer (Fig. 5(c)) (thermocouple, probe diameter 25 × 50 mm, length 50 mm, maximum temperature +100°C) was used to record temperature variations, while a high-sensitivity seismic accelerometer (Fig. 5(b)) (model 393B12, 10 V/g, 0.15–1 kHz) records vibrations for frequency identification. The accelerometer transmitted an analog signal to the dynamic acquisition unit via the black cable (Fig. 5(b)), which was then converted into a digital signal through the long orange cable to be subsequently transmitted to the PC (Fig. 5(d)). The thermometer was connected to the static acquisition unit using the thin red and white wire (Fig. 5(c)), while the power supply for the acquisition units was ensured through the long orange cable (Fig. 5(d)). To simulate colder environmental conditions, temperature reductions were introduced, allowing for an assessment of the material-dependent effects of temperature variations on the system natural frequencies.

4 Results

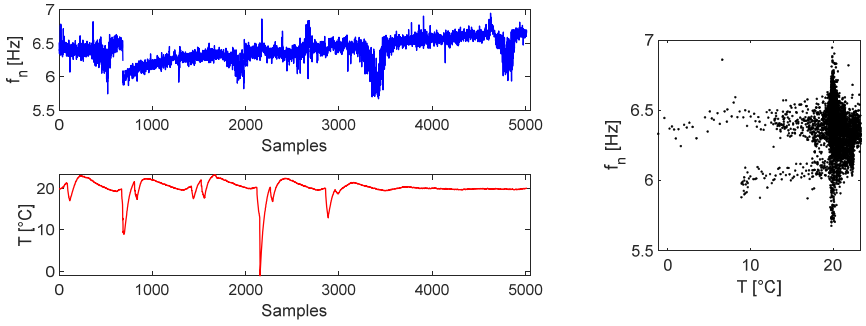
Fig. 6-Fig. 8 show the data acquired during the experiments. From the analysis of the results, from the historical time series, it appears that the frequency behaviour changes partially with temperature variations. Specifically, it seems t that frequency shifts occur with temperature changes. In the scatter plots, there are clusters where the data points are concentrated. These clusters correspond to the most frequent temperatures, as it was an indoor laboratory experiment, and the system remained between 18°C and 20°C for most of the time. Therefore, the relationship between temperature and frequency becomes more apparent only during periods of temperature fluctuation. When the temperature drops below 20°C, a clearer trend begins to emerge, suggesting a correlation between temperature and frequency. In the case of concrete, configuration (II), when comparing the experimental data (Fig. 7) with the data from the real structure (Fig. 1), a significant discrepancy is observed between the scatter plots. Aside from potential outliers, the bilinear trend seen in the real structure does not appear in the laboratory experiment. This suggests that the only variable considered in this experiment during the temperature variation, namely the mass, cannot explain this relationship. Consequently, other factors that were neglected in this study may play a crucial role. Furthermore, it is possible that temperature is not the only environmental factor influencing the frequency behaviour variation in concrete. For steel (Fig. 6), configuration (I), excluding the point cloud for the most frequent temperatures, it is observed that below 17°C, as temperatures approach zero or lower, the behaviour becomes linear: frequencies decrease as ambient temperature increases. This trend is very similar to that observed in the steel bridge (Fig. 1). It can likely be attributed to the fact that metallic materials are less affected by other environmental variables, such as humidity, making temperature the most significant environmental factor. There-

fore, in the variation considered, namely frequency-temperature, the fact of having a different density, or rather a different mass, could play an important role.



(a) (b)

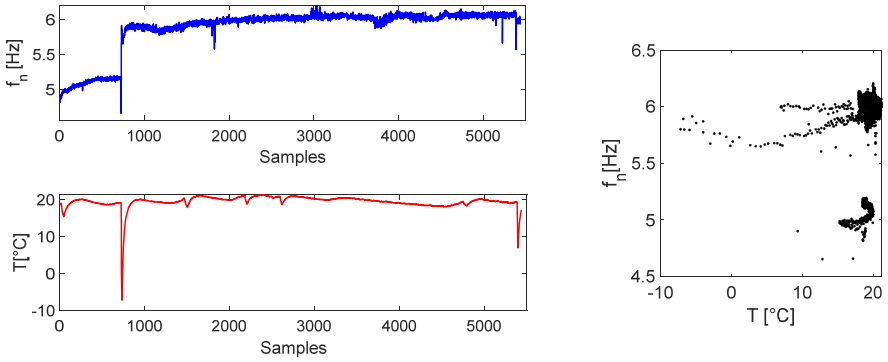
Fig. 6 Results for setup (I) (steel): (a) Time series of natural frequency and temperature, and (b) natural frequency and temperature scatter plot



(a) (b)

Fig. 7. Results for setup (II) (concrete): (a) Time series of natural frequency and temperature, and (b) natural frequency and temperature scatter plot

Finally, in the case of masonry (Fig. 8), configuration (III), the scatter plot shows two clusters of points concentrated around 20°C, as expected. Below 15°C, a slight decrease in frequency is observed as temperature decreases, while below about 4°C, an opposite trend emerges, with frequencies increasing as the temperature drops. Focusing on this part of the scatter plot, a certain similarity is observed between the system studied in the laboratory and the two examples of cultural heritage shown in Fig. 2 and Fig. 3. However, despite these similarities, the behaviours still differ significantly, suggesting that the assumptions made for the experiment are insufficient to fully explain this relationship, although they do partially replicate it. This indicates that, in this case as well, other environmental variables, as well as factors such as structural type, geometry, constraints, etc., need to be considered. The discrepancy between the observed trends may, in fact, be due to the complexity of the two systems shown in Fig. 2 and Fig. 3, which contrast with the structural and geometric simplicity of the system used in the laboratory.



(a) (b)

Fig. 8. Results for setup (III) (masonry): (a) Time series of natural frequency and temperature, and (b) natural frequency and temperature scatter plot.

5 Conclusions

This study explored the effect of environmental variables, particularly temperature, on the dynamic behaviour of structural systems composed of different materials. The experimental findings demonstrate that temperature fluctuations notably influence the natural frequencies of the structures. For steel, the temperature-frequency relationship followed a linear pattern, which aligns with the behaviour seen in real steel structures. This suggests that temperature could be a dominant factor influencing frequency in metallic materials. However, for concrete, the laboratory results showed a significant discrepancy when compared to data from real structures, indicating that temperature alone is insufficient to explain the frequency variations in concrete. In the case of masonry, the relationship was more complex, with a decrease in frequency as the temperature dropped, followed by an increase once the temperature fell below a certain threshold. Although this trend was similar to the behaviour observed in cultural heritage structures, the differences highlight the importance of considering additional variables such as structural type, geometry, and boundary conditions. These factors are likely to play a critical role in determining the frequency response, and including them in the analysis would make the representation of the problem under consideration more comprehensive. Thus, the results emphasize the need to consider environmental factors in SHM to improve diagnostic accuracy. However, temperature alone cannot explain all possible variations, suggesting that a more comprehensive approach is needed, one that includes both more environmental and structural factors to improve the reliability of SHM systems and better distinguish between normal variations and potential structural damage scenario.

In conclusion, distinguishing between changes caused by environmental conditions and those indicative of structural damage remains a fundamental challenge in ensuring the effectiveness of SHM techniques. Further research is needed to refine SHM methodologies and improve the ability to detect and manage structural issues with greater precision.

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