DECLARATION

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

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Dedication page (fully optional)

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ABSTRACT

The conservation and rehabilitation of the cultural heritage of a society, ensures the prevalence of traditions that generate a collective memory. For these reasons this project is presented as a response to the need to monitoring the structures in order to define their current state and generate information that in the long term can elucidate changes in the characteristics of the structure. The current project refers to the structural health monitoring that is being carried out in the Basilica of the Assumption of the Virgin Mary, or the Bazilika Nanebevzetí Panny Marie located in Stará Boleslav - Czech Republic.

Considered as one of the most important monuments of early Baroque style in Bohemia, the Church has been under study several times as part of the project “Monuments in Motion”. Project mainly focus in long-term dynamic loads as a factor that can decrease safety and affect the durability. Even though, the magnitude of the amplitudes of technical seismicity loads are not high, the continued exposure to them contribute to degradation processes.

‘The Monitoring of Historic Buildings Exposed to Technical Seismicity and Other Dynamic effects’ is a investigation that aims to present a methodology to relate the information collected from the monitoring with stress concentration in the elements and its change over time. To accomplish this objective, is presented the basic concepts of non-destructive tests and modal testing. Is also developed the importance of the application of monitoring in historical monuments and a brief state of art from some structures where this tests where done.

The church has been monitored in three times. In 2019, was the first campaign to evaluate the structural behavior of the asset that in this moment had some evident damage as multiple crack in vaults and other elements. The second monitoring measurement was done in 2021 after the retrofitting of the structure in order to determine the quality of the intervention and the improvement of the performance of the building. Finally, the third structural health monitoring started on April 2022 to do a regular inspection by comparing the new results with the previous studies.

Moreover, in this project is presented the results from each of the monitoring campaigns and the comparison with the last values. A statistical study is presented and a rain flow counting to generate an extrapolation of the values obtained in these 3 weeks of SHM. The amplitudes determined are used in a FE model to evaluate the concentration of stresses and the influence of the technical seismicity after two years.

For further studies, the development of a FE model of all the structure is being prepared where the vibration tests will allow a calibration and would decrease the uncertainties.

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RESUMO

Zachování a obnova kulturního dědictví společnosti zajišťuje zachování tradic, které vytvářejí kolektivní paměť. Z těchto důvodů je tento projekt předkládán jako reakce na potřebu monitorování struktur s cílem definovat jejich současný stav a generovat informace, které v dlouhodobém horizontu mohou objasnit změny charakteristik struktury. Tento projekt se týká monitorování stavu konstrukcí, které se provádí v Bazilice Nanebevzetí Panny Marie nacházející se ve Staré Boleslavi - Česká republika.

Kostel, který je považován za jednu z nejvýznamnějších raně barokních památek v Čechách, byl již několikrát zkoumán v rámci projektu "Památky v pohybu". Projekt se zaměřuje především na dlouhodobé dynamické zatížení jako faktor, který může snižovat bezpečnost a ovlivňovat životnost. Přestože velikost amplitud technických seismických zatížení není vysoká, jejich trvalé působení přispívá k degradačním procesům.

Šetření "Monitorování historických budov vystavených technické seizmicitě a dalším dynamickým účinkům" si klade za cíl představit metodiku, která umožní propojit informace získané z monitorování s koncentrací napětí v prvcích a její změnou v čase. K dosažení tohoto cíle jsou představeny základní koncepty nedestruktivních zkoušek a modálního testování. Dále je zde popsán význam použití monitorování v historických památkách a stručný stav techniky u některých konstrukcí, kde byly tyto zkoušky provedeny.

Kostel byl monitorován ve třech případech. V roce 2019 proběhla první kampaň za účelem vyhodnocení chování konstrukce objektu, který v tomto okamžiku vykazoval některá zjevná poškození v podobě četných trhlin v klenbách a dalších prvcích. Druhé monitorovací měření proběhlo v roce 2021 po modernizaci konstrukce s cílem zjistit kvalitu zásahu a zlepšení vlastností budovy. A konečně třetí monitorování stavu konstrukce bylo zahájeno v dubnu 2022 s cílem provádět pravidelnou kontrolu porovnáním nových výsledků s předchozími studiemi.

Kromě toho jsou v tomto projektu prezentovány výsledky z každé z monitorovacích kampaní a srovnání s posledními hodnotami. Je prezentována statistická studie a počítání dešťových toků pro vytvoření extrapolace hodnot získaných v těchto 3 týdnech SHM. Zjištěné amplitudy jsou použity v modelu FE k vyhodnocení koncentrace napětí a vlivu technické seismicity po dvou letech.

Pro další studie se připravuje vývoj FE modelu celé konstrukce, kde vibrační zkoušky umožní kalibraci a sníží nejistoty.

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RESUMEN

La conservación y rehabilitación del patrimonio cultural de una sociedad, asegura la prevalencia de las tradiciones que generan una memoria colectiva. Por estas razones este proyecto se presenta como una respuesta a la necesidad de monitorear las estructuras, para definir su estado actual y generar información que a largo plazo pueda dilucidar cambios en sus características. El presente proyecto se refiere al monitoreo estructural que se está llevando a cabo en la Basílica de la Asunción de la Virgen María, o la Bazilika Nanebevzetí Panny Marie situada en Stará Boleslav - República Checa.

Considerada como uno de los primeros monumentos más importantes del estilo barroco en Bohemia, la iglesia ha sido objeto de estudio en varias ocasiones como parte del proyecto "Monumentos en movimiento". El proyecto se centra principalmente en las cargas dinámicas a largo plazo como factor que puede disminuir la seguridad y afectar a la durabilidad. Aunque la magnitud de las amplitudes de las cargas sísmicas técnicas no son grandes, la exposición continuada a las mismas contribuye a los procesos de degradación.

El monitoreo de edificios históricos expuestos a sismicidad técnica y otros efectos dinámicos es una investigación que pretende presentar una metodología para relacionar la información recogida en la monitorización con la concentración de tensiones en los elementos y su cambio en el tiempo. Para lograr este objetivo, se presentan los conceptos básicos de los ensayos no destructivos y los ensayos modales. También se desarrolla la importancia de la aplicación de la monitorización en monumentos históricos y un breve estado del arte de algunas estructuras donde se han realizado estos ensayos.

La iglesia ha sido monitoreada en tres ocasiones. En 2019, fue la primera campaña para evaluar el comportamiento estructural del bien que en ese momento tenía algunos daños evidentes como múltiples grietas en bóvedas y otros elementos. La segunda medición de monitoreo se hizo en 2021 después de la readaptación de la estructura para determinar la calidad de la intervención y la mejora del rendimiento del edificio. Por último, la tercera monitorización de la salud estructural se inició en abril de 2022 para realizar una inspección periódica comparando los nuevos resultados con los estudios anteriores.

Además, en este proyecto se presentan los resultados de cada una de las campañas de monitorización y la comparación con los últimos valores. Se presenta un estudio estadístico y un conteo de flujo de lluvia para generar una extrapolación de los valores obtenidos en estas 3 semanas de SHM. Las amplitudes determinadas se utilizan en un modelo FE para evaluar la concentración de tensiones y la influencia de la sismicidad técnica después de dos años.

Para estudios posteriores, se está preparando el desarrollo de un modelo FE de toda la estructura donde las pruebas de vibración permitirán una calibración y disminuirán las incertidumbres.

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CHAPTER I INTRODUCTION

1.1 MOTIVATION

Long term dynamic loads represent a factor that could compromise the durability, and therefore the safety, of historical monuments. Traffic induced vibrations generally are not an immediate hazard, however, as cyclic loads they could lead progressive damage over time, and the exact level of damage will depend on the mechanical characteristics of the structures (Bongiovanni et al., 2011a). The influence of these vibrations in a structure will depend on the source, frequency, duration, magnitude and their variation over time. The continued exposure can increase the degradation of the materials or the joints (Urushadze et al., n.d.-a).

The assessment of the alteration of the characteristics of the built structures is a multidisciplinary task (Bayer et al., 2021a), even more so when it comes to historic monuments. The understanding of the properties and materials in historic monuments usually requires more time investment and technology tools that can provide results without damaging the elements. Therefore, nondestructive testing is widely applied here.. In recent years, the study of the structural dynamics through experimentation has given a major contribution to understanding and controlling the phenomena induced by vibrations (EWINS, 2009). The preceding statements are the base for this project that aims to evaluate the effects of traffic and ambient vibrations using information collected by the monitoring of the Basilica of the Assumption of the Virgin Mary in Stará Boleslav, Czech Republic.

The statistical analysis presented aims to predict the evolution of the characteristics, properties and behavior over time of the existing structures. The monitoring can also support preventive or reinforcement measures to safeguard the heritage in case of necessity to stop slowly progressing deterioration..

1.2 AIMS

GENERAL OBJECTIVES

The main objective of the study is to determine the effects of induced vibrations on historical structures through nondestructive testing and monitoring, which in turn can lead to the prediction of the evolution of their characteristics, properties, and behavior over time.

SPECIFIC OBJECTIVES

- Simplify the identification and diagnosis methods commonly used, through the analysis of experimental values of dynamic response to increase their accuracy.

- Identify changes in the vibration characteristics of the structure in time through the analysis of the signals obtained in-situ to analyze the structural behavior.

- Estimate the stresses in the structure caused by the vibrations throught the inclusion of the measured deformations in the numerical model

- Analyze the long-term structure testing data to identify the sources of vibration that can lead or accelerate the process of degradation.

- Propose a procedure based on the monitoring measurements of historical buildings that are subjected to long- and short-term dynamic effects for the assessment of the vulnerability that allows prediction of the behavior of the structures and to take preventive measurements to avoid or decrease the sources of vibrations.

1.3 SCOPE

The present project is a response to the need of evaluation of stress concentrations by monitoring structures. This proposal will allow assessment of the current state of buildings and estimation of their future behavior if they continue to be subjected to the same dynamic loads. A simplified methodology is proposed with the aims of verifying the results of the numerical modeling, allowing the characterization of the properties of the structure and providing the tools for calibration of the model with the data collected from the monitoring.

1.4 JUSTIFICATION

As Ellis, (1987) mentioned, the increment in number and in size of the traffic was a problem that needed attention. At the time, most of the studies were developed for modern structures in which the effects of the technical seismicity were not relevant for the structural performance. The topic has become important in the field of structural engineering to quantify serviceability and also to ensure the comfort of the habitants of the buildings.

This project proposes monitoring as an option to evaluate the effects that dynamic loads have in historic structures. Long term monitoring of this type of loading is crucial due to the fact that the effects of dynamic loading, strongly fluctuant by nature, are difficult to determine. Additionally, the geometry and complexity of the historic structures limit the accuracy of the numerical models where modal testing can be used to decrease the effort and ensure an appropriate result. (Rücker et al., 2006)

Furthermore, for the identification of the global and local properties, condition monitoring provides continuous values that suggest the actual state of the asset and make an accurate estimate of the structural condition in the future. With long term data collection, the presence of damage can be identified; an important task to have a precise definition of the structural behavior. (Lorenzoni et al., 2013; Rücker et al., 2006)

The statistical analysis can provide the number of load cycles and the level where the loads are applied which is crucial to establish the damage type that can be induced by the development of micro cracks (Bongiovanni et al., 2011a).

1.5 CONCEPTUAL FRAMEWORK

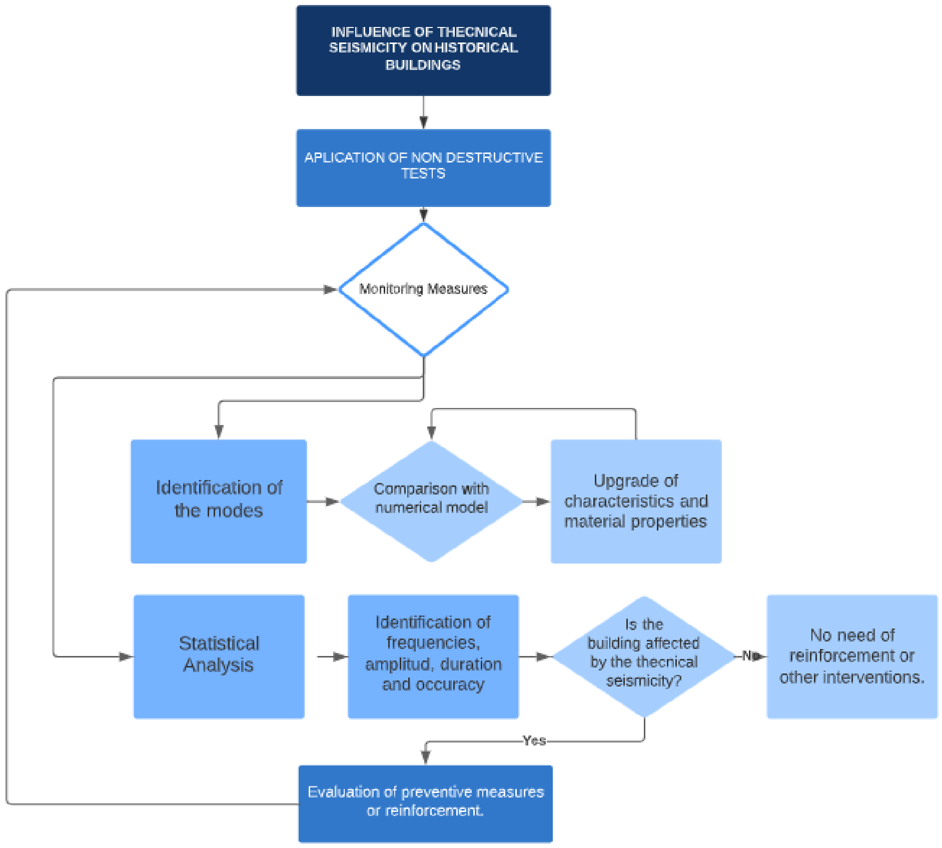


Figure 2-1 Methodology framework

CHAPTER II THEORETICAL FRAMEWORK

Is presented as theoretical framework a list of definitions to develop a friendly environment that allows the understanding of the choices made in this project. As well, concepts of the tests are developed through numbering the advantages and disadvantages of their application. Moreover, the importance of nondestructive testing and structural health monitoring in historical monuments is presented in order to justify their relevance in this field.

2.1 NON-DESTRUCTIVE TESTING

Non-destructive testing in structural analysis and damage analysis has been successfully applied in the field of heritage preservation, as novel techniques. Some of the techniques, combined with methods of data processing, will help to characterize and solve problems efficiently and in an economic way.

NON-DESTRUCTIVE TESTING FOR STEEL

For structural and damage identification in steel elements, high frequency ultrasonic technologies are commonly used. Properties, such as thickness, can be determined. In the case of damage identification information of holes and flat separations as cracks can be pointed. Radiography can also give an overview of pores, blowholes and inclusions of different materials. These reasons make it important in historic buildings, where plates and nails can be found in the analysis of the sections. An example of the identification of damage by dynamic parameters in steel structures can be found in The Guideline for Structural Health Monitoring (Rücker et al., 2006), where a bridge span is submitted to artificially gradual damage in order to simulate the development of cracks at welding points.

NON-DESTRUCTIVE TESTING FOR REINFORCED CONCRETE AND PREESTRESSED STRUCTURES

For reinforced concrete and prestressed structures, the quantity and distribution of reinforcement bars are one of the most important requirements when the strength of the elements is needed. This information can be taken from the combination of different tools. Magnetic methods can help when the reinforcement is placed near the surface, otherwise radar will give better results. Drilling and endoscopic investigation can also be proposed as minor destructive tests to give a complete description of the elements (Rücker et al., 2006).

NON-DESTRUCTIVE TESTING FOR MASONRY

In the case of masonry, radar has become an important tool when it has widespread damage. In masonry, the non-destructive techniques are usually implemented with the objective of characterizing elements by knowing some properties, such as thickness, alignment, porosity, hollow cavities or location of metal ties. If the structural properties of clay bricks or stones are needed, ultrasound, endoscopy or micro seismic tests can be applied to generate approximate values for compressive strength and homogeneity. The values to characterize masonry density and other properties from velocity propagation can be obtained by relations proposed in different codes and studies as (Orenday et al., 2021).

In the other materials, such as timber, the electric methods can provide information of moisture content.

As an inspection approach there are field tests that provide information for the structural characterization and can be considered a monitoring task when they are used in a regular manner or as an intermittent observation. These could be classified as static tests or dynamic tests. The first classification is mostly used to check the load bearing capacity of the structure, while the dynamic test objective is the determination of the dynamic properties of the structure and its performance under the dynamic loads. (Rücker et al., 2006)

STATIC TEST

Static tests are used to identify the loads that are placed in a structure in a certain manner that do not cause dynamic effects. These are suitable to identify the behavior, carry out a diagnosis or to proof the structures, aims that will give the subclassification of the static tests. Static tests represent a good option because the commercial tools for analysis are usually based on linear theory; moreover, most of the assumptions to simplify the system is to make it work in the linear region. (Casciati, 2005)

Behavior tests could allow the identification of more accurate analytical methods for design and evaluation of structures. Therefore, they will provide a characterization of the loads as they are distributed among the elements, which is information needed for calibration processes.

Diagnostic tests are developed to recognize the effects of interactions between components. Furthermore, if they are applied appropriately, they will allow the sources of distress to be located.

Proof tests are carried out to establish safe load-carrying capacity. In this case, the structure is subjected to static loads that are gradually increased to cause large responses in the asset. The gradual increase of the load will ensure that the loads do not go beyond the limit of the linear static behavior of the elements where permanent damage could be caused in the structure. (Rücker et al., 2006)

DYNAMIC TEST

Dynamic systems are characterized by stiffness, damping and mass. Defining them as damped or undamped will depend on the presence or absence of energy dissipation in each cycle of vibration. (Ferreira, 2007). For the determination of dynamic responses, two approaches can be applied depending on the nature and properties of the excitation.

The results of the dynamic tests are obtained by the transformation of the input signals (u) into output signals (y) by the application of a scalar transfer function (G), under initial conditions (Casciati, 2005). Depending on the characterization of the loads the excitation of the dynamic response will be determined by a deterministic or stochastic approach. If the excitation is characterized in time, the loads can be described as deterministic. In the case of random excitation, the analysis will include probabilistic concepts. (Chopra, 2017)

Furthermore, dynamic loads are often complex due to their characteristics and spatial distribution, reasons why their implementation demands high computational power. Dynamic tests can be also subclassified as: stress history tests, dynamic load tests and modal testing (Rücker et al., 2006). This work will give more attention to the modal testing information in order to build a theoretical framework for the results presented.

- **Stress history tests**

Stress history tests are applied to recognize zones of accumulation of experimental stresses – called 'hot spots' – caused in dynamically highly stressed regions in the structure. To reach this aim, a large number of sensors is needed and the recordings are taken under normal operating conditions. These types of tests are usually applied when the complexity of the structure and the dynamics loads do not allow an accurate numerical simulation.

- **Dynamic load tests**

Dynamic load tests are carried out by the measurement of strains in structural elements that are important for the design. Their accuracy will depend on the validation of the information provided and as a result will lead to the determination of controlled increment of traffic loads. Dynamic load tests can be subdivided further based on the number of input signals and the element type of the outputs. Casciati, (2005) distinguishes four cases:

1) SISO: single input - single output.
2) MISO: multiple input - single output.
3) SIMO: single input - multiple output.
4) MIMO: a multiple input - multiple output.

	Method	Type of formulation	Type of DOF	Type of estimates	Number of inputs/outputs
Frequency Domain	Peak Picking	Indirect (Modal)	SDOF	Local	SISO
	Circle-fit				
	Inverse				
	Dobson				SISO/SIMO
	Nonlinear LSFD		MDOF	Local Global	SIMO MIMO
	Orthogonal Polynomial				
Tuned-sinusoid	Mau		SDOF	Local	SISO
	Asher's		MDOF	Global	MIMO
Time Domain	Complex Exponential		SDOF	Local	SISO
	LSCE		MDOF	Global	SIMO/MIMO
	Ibrahim				MIMO
	ERA				
	ARMA	Direct			

Figure 2-1 Classification of system identification algorithms. (Caetano, 2000)

MODAL TESTING

In-situ modal identification tests are implemented as an important tool to determinate the extent and nature of the vibrations that are affecting a structure, the accuracy of a theoretical model or the predictions of various dynamic phenomena, and for the determination of some material properties such as the damping capacity, fatigue endurance and friction. (EWINS, 2009). In addition, determination of modal properties results can be used for damage identification processes (Rücker et al., 2006).

Measurements are made by two different procedures, depending on the aims of the application. To measure vibration forces the test is made on the asset while continues operation. On the other hand, when the objective is to know the accuracy or to validate a model, the test consists of vibrating the structure with a known excitation. This will demand much more controlled conditions and the interruption of normal operation (EWINS, 2009).

Within the literature, the classification of the modal tests diverges, depending on the experimental techniques and the type of vibration. According to Ferreira (2007), due to the experimental methods applied the subdivision will be:

- **INPUT – OUTPUT VIBRATION TESTS**

Input-output vibration tests use techniques based on the control of the excitation force and measurement of the vibration response of the structure in selected points.

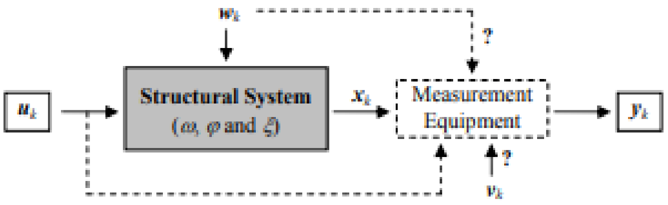


Figure 2-2 Input-output technique scheme. (Ferreira, 2007)

At the same time, this can be classified because of the type of formulation, the number of degrees of freedom and the number of inputs or outputs. The number of excitation and measurement points will be important to reach a certain level of accuracy.

- According to the formulation of the tests, some assumptions can be made as linearity, orthogonally property of the mode shapes and proportionality between damping, mass and stiffness. The formulation will also allow to uncouple the structural response in modal contributions.

- **OUTPUT ONLY TESTS**

In output only tests, only the response of the structure is measured. Also known as Operational Modal Analysis (OMA), output only tests are conducted under service conditions. They are carried out under the assumption that the excitations are random in time and in physical space for the structure.

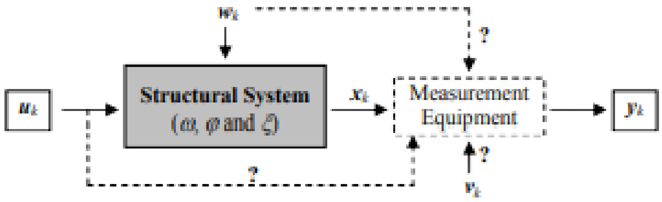


Figure 2-3. Output only technique scheme. (Ferreira, 2007)

The main assumption will be that the excitation of the virtual system is the ambient vibration. Due to its nature, the records of information will include the modal contribution of ambient forces and some noise signals from unwanted sources.

Two main groups of these techniques can be distinguished depending on the domain where the data is described, frequency domain or time domain. Defined as non-parametric or parametric methods correspondingly.

FREE VIBRATION TESTS In the free vibrations tests, the structure is subjected to an initial deformation and released.

According to the type of excitation of the structure, the modal testing can be named as 'Ambient Tests' or 'Forced Vibration Tests'. Ambient vibration tests are carried out under operational conditions, the dynamical loading will be created by the presence of wind, weather, traffic, etc. The excitation can be defined as stochastic with a broadband spectrum. The advantages of the application of this test are that they can be applied in bigger structures and their aims are accomplished relatively quickly and economically. On the other hand, because the response given by the material is very small, due to the nature of the excitation, the sensors used must have high sensitivity. (Foti et al., 2012a)

Force vibration tests need the inclusion of regulated excitations, usually impulses provided by tools such as an impulse hammer or drop hammer. The selection of the type of vibration input will depend on the conditions and the dynamic characteristics of the structure. In contrast to the ambient vibration tests, these are more expensive due to the equipment needed, the disruption of activities and the control of the conditions in-situ. The advantage is the accurate information obtained for the determination of the modal characteristics of the asset (Rücker et al., 2006)

To enumerate the different applications of the modal testing, it is needed to mention that in all the cases is used to obtain a mathematical model. The difference will arise in the subsequent use of the model. The determination of natural frequencies and the description of the mode shapes are needed as initial knowledge, however depending on the purpose the level of accuracy can increase. The applications identified by EWINS (2019) are mentioned below:

- **Validation of a theoretical model**

This application is based on the comparison of the values of vibration obtained from the modal testing and the results of the finite element model. The validation of theoretical models by modal testing is commonly used to verify the modelled predictions of the behavior of the structure when itis submitted to complex excitations. The information needed to begin has to be accurate enough to correlate with the model results. It has to be mentioned that, from this level of investigation, it is not possible to obtain damping.

- **Correlation**

The correlation between the experimental measurements and the theoretical results is done by a process where the two sets of data are compared. Its main objective is to identify the causes of the discrepancies between the measurements after comparing them quantitatively. This application will demand a high-level of accuracy in the data taken from the modal test.

- **Sub-structuring process**

The sub-structuring process is used for complex structures. It consists of the production of a mathematical model of a component that later can be assembly as an aggregate in a structural model. As in the previous applications, the natural frequencies and the modal shapes are needed, but also the modal damping factors. The accuracy needed means that certain modes within the range of interest cannot be ignored.

- **Determination of the effects of modifications.**

It can be considered as a variant of the previous use, implies the generation of a model whose results will predict the effects of a certain modification on the asset. One consideration is that the information referred to the rotational degrees of freedom is needed. Theoretically, moments, forces, rotational displacements and translational displacements are determined, however they are generally avoided in the experimentation campaigns because they are more complicated to measure. Nevertheless, these values are important to couple the models.

- **Determination of forces.**

Force determination is necessary to build knowledge of the dynamic forces that are causing vibration. For this purpose, the forces are deduced by transfer functions that combine the effects measurements and a mathematical description.

2.2 MONITORING OF STRUCTURES

Implementation of permanent and automated monitoring in a structure develop the information necessary to understand the current state, the future performance of the asset or its components and the effects of the loads. Therefore, the temporal and spatial change of the load related to the strain monitoring can lead to having a damage analysis (Rücker et al., 2006).

Monitoring can be continuous, cyclic, event or load dependent. Permanent monitoring refers to the use of sensors that will provide continuous measurements and is executed when the treatment of extensive information is required in order to measure the effects and their allocation. For the identification of load exceedance, inactive monitoring could be adequate using a threshold value, a tool that will allow a reduction of the amount of information collected.

STRUCTURAL HEALTH MONITORING

The objective of structural health monitoring is to not only analyze the actual state of the structure, but to track the structural integrity and assess the nature of damage. The most widely used methods to record information include the employment of vibration sensors as velocity meters and accelerometers. (M Todorovska & Trifunac, 2008a)

These studies are usually carried out when there is overloading or when the structure is surpassing its operational life. The analysis of data collected from structural health monitoring can lead to the implementation of preventive measures, such as the reduction in the exposure to the load or the improvement of the structural resistance.

- **Purposes**

Load observation requires knowledge of the behavior of the system, which can be established by a structural model or by the application of experimental methods. Identification and characterization of the load ensures an accurate numerical model, with realistic statements as to the determination of the fatigue or the residual time life.

Long term monitoring of load effects become important when they cannot be exactly determined for distinct reasons such as the complexity of the structures or the extremely fluctuant nature of the load itself.

The effects can be measured in a global or local manner. Structural properties at a local level are usually monitored when damage has already been identified or when the element is exposed to a new or different loading condition. Success in identifying structural changes in single components (local effects) will depend on the location of the measurement points. (Rücker et al., 2006).

According to Rücker (2006), the reactions of the existing loads can be used for: verification of existing load models, long term statistical analysis, determination of load collective and dynamic factors by the characterization of the load, improvement of load models by the effective application of loads in elements where its effect is critical, identification of problems related to environmental loading as temperature effects or dynamic loading, generation of preventive actions that can reduce load effects.

Moreover, monitoring of structural health can give an early warning, during or after natural or human induced hazards. This analysis can be done even before an inspection is possible and can decrease the loss of life and number of injuries during an emergency response (M Todorovska & Trifunac, 2008a). In terms of diagnosis, the application of SHM allows the detection of the location and extent of damage not visible to casual observation caused by extreme events or due to gradual deterioration and may avoid expensive and invasive interventions. (Farrar & Worden, 2007)

2.3 MONITORING OF HISTORICAL STRUCTURES

The complex shape of many historical monuments and the difficulties to characterize the materials that are present in their different elements make monitoring an important tool to develop knowledge about these assets. Components, materials, deformations or degradation processes can be characterized with the implementation of methods of monitoring that record the behavior in a determined time lapse.

Moreover, intrusions in properties of cultural interest are usually limited to minimum interventions to ensure safety and durability, these criteria being the most important guidelines to apply in all stages of analysis. The steps of analysis include material study, structural analysis, construction to maintenance, phases that can be related to “anamnesis, diagnosis, therapy and controls” names more commonly used in medicine but that show a clear way to proceed (ICOMOS, 2005). The long time lapses since most of the structures were built, and the lack of information of previous interventions, could require the extraction of a great number of samples which can affect the integrity of the structure. Also, it would require a large investment of resources during the sampling and in the repair of the elements involved.

Seismometers and displacement transducers are usually used for non-destructive tests and monitoring in historical monuments. The information recollected is analyzed performing statistical and spectral analysis. (Bongiovanni et al., 2011b)

The complexity of the structures, due to the geometry and the constant addition of aggregates, demand sophisticated models and high computer power. Monitoring information can help to simplify the numerical models by the correlation of certain parameters of the model – natural frequencies and mode shapes – with the ones obtained experimentally, increasing the efficiency by avoiding complicated shapes in the finite element models. (EWINS, 2009)

After the validation of the simulations, the future behavior of the structure obtained as a result of it can be assumed as accurate. With this aim, long term monitoring can be used to provide evidence of gradual deterioration or variation of the loads over time. Finally, during the construction, SHM will validate the quality of the intervention and the level of improvement in the performance of the building.

The experience in the application of structural health monitoring has become greater in previous years, helping with the implementation of preventive measures to reduce loads or vibration exposure; e.g. the determination of acting live loads and temperatures can grow knowledge of maximum values of storing in certain hours. (Rücker et al., 2006)

Many case studies are available with the aim to validate the importance of monitoring. Some of them are also carried out under laboratory conditions to determine certain characteristics such as stiffness change due to static loading where monitoring is applied to correlate modal parameters with a finite element method or even further to identify damage (Bayer et al., n.d.).

Ambient vibration testing, due to its advantages of cost and easy application, is one of the more commonly used techniques, such as in the Margherita Palace after the L'Aquila earthquake (Cimellaro et al., 2012a), in the tower of the Provincial Administration Building in Bari, Italy (Foti et al., 2012a) and in the Assumption of the Virgin Mary in the Czech Republic where the influence of technical seismicity is part of the scope (Urushadze et al., n.d.-a) (Bayer et al., 2021a).

Furthermore, monitoring techniques have evolved in recent years, giving more options to collect information. For instance, photogrammetry can be mentioned as a complete, portable, flexible and economic method to record architectural information but also to satisfy the necessities of documentation of cracks and surface deterioration processes. (Armesto et al., 2008)

Monitoring of the integrity of the structures, in new and old buildings alike, can lead to the early detection of damage and allowing the opportunity to react appropriately. Therefore, it can be said that this is a tool aligned with the objective of conservation that includes permanent maintenance (ICOMOS, 1964)

For the determination of the type of monitoring, there is not a specific rule as in the other stages, although a previous analysis and delimitation of the aims of the instrumentation will ensure an effective and economic method. SHM of tangible cultural heritage also helps to keep updated its performance giving a

2.4 TRACED VALUES AND EXPERIMENTAL IDENTIFICATION OF STRUCTURAL PARAMETERS

Measure of vibration velocities and accelerations is used for description of mass forces or strains when a structure is submitted to vibrations such as explosion loads, collision loads and others. Moreover, the static and dynamic effects of variable loads, such as traffic, can be also determined by measuring deformation in terms of strains or displacements and comparing them with previous values.(Rücker et al., 2006)

Most commonly used techniques are based on natural frequencies, modal strain energy methods, mode shape, operational deflection shapes, residual force vector methods, frequency response functions, statistical methods. (Rücker et al., 2006)

The monitoring measurands can be static or dynamic. The measurements of displacements and environmental effects are considered as static or quasi static since they present slow variation over time.

As examples of static monitoring measurements, traced values can be mentioned, such as deflection, out of plane data, settlements, inclination or crack width and length. The quasi static are mostly environmental effects, such as corrosion, humidity, temperature and others. As important requirements for the analysis of information, the determination of standard deviation, the recording of large amplitudes over time, and the definition of adequate values for a threshold will be needed.

Continuous monitoring of cracks gives a certain notion of the behavior of the structure and reveals a critical state of the asset when the limits are surpassed. By the documentation of increment in number and dimensions of cracks, elements that are suffering high concentrations of stresses are recognized allowing early damage detection.

Dynamic values, such as mode shapes and natural frequencies, are evaluated with the aim of correlation beside the properties of the structure and are determined by an experimental modal analysis. In the case of natural frequencies, they are obtained approximately by the selection of peaks in the power density spectrum. Moreover, for the identification of mode shapes, simultaneous information in different points will need to be recorded. Since this work is focusing its attention into an environmental modal test it needs to be mentioned that the values of the operational mode shapes will be similar to the mode shapes for the natural frequencies (natural mode).

To verify the accuracy of the values obtained is important to do a previous experimental examination or numerical simulation. This previous study allows to choose natural frequencies, operational mode shapes, location and number of measured points to achieve the aims of the application of the monitoring. Precision of the results will also depend on the treatment of the data as the elimination of interferences or sources of vibration that are out of scope.

2.5 ENVIROMENTAL EFFECTS ON LOADING CONDITIONS

Multiple studies have proved that temperature can influence changes in modulus of elasticity, as well as boundary conditions. The changes in the dynamic response can come from the loading source, wind, traffic, waves, and earthquakes, among others(Ferreira, 2007).

Therefore, the inverse proportionality of the resonant frequencies with excitation amplitude, and the proportionality of the damping ratios with the amplitude where mentioned by Maeck et al., (2000) for concrete structures.

Moisture absorption can be important to detect in masonry structures. Depending on the porosity and absorption capacity of the elements, moisture can increase the mass and change the stiffness (Ferreira, 2007). In opposition to this, the study of a bridge by Peeters (2000), found that the humidity does not modify the characteristics because of the nature of the asphalt and the drainage conditions of the structure.

In the case of temperature, the study of a few bridges under different weather conditions exhibits an increment of the first frequency up to 4%. One of these studies attributed this variation to the layer made of asphalt when its temperature goes below zero. On the other hand, the measures of wind characteristics, humidity and rainfall in this specific case did not appear to be correlated with the eigenfrequencies. (Peeters, 2000)

Due to the reasons mentioned, Ferreira (2007) suggests the inclusion of the environmental effect in the numerical model as a filter that will return the definitive values for the parameters that will be used for damage identification. For the inclusion of this effect, the relation between the environmental conditions and the loading effects has to be clearly defined by a model that also give a confidence interval to warranty the damage detection.

2.6 STATE OF THE ART SHM AND NDT APPLICATION

TITLE	AUTHORS		TEST APPLIED	REMARKS
AMBIENT VIBRATION TESTING, DYNAMIC IDENTIFICATION AND MODEL UPDATING OF A HISTORIC TOWER	(Foti et al., 2012b)	-	Operational Modal Analysis (OMA)	Evaluation of structural conditions of the Tower of the Provincial Administration Building in Bari, Italy to predict performance under static and dynamic loads as earthquakes. The study includes full-scale ambient vibration testing, modal identification from ambient vibration responses using three different identification methods, finite element modeling and dynamic-based identification of the uncertain structural parameters of the model.

			The aim of the study is to develop a 3D finite element model able to match the OMA results.
DAMAGE DETECTION AND LOCALIZATION IN THE SPACE OF THE OBSERVED VARIABLES	(Casciati, 2005)	- Impulse excitation (instrumented hammer) - Controlled excitation (shaker) - Operational Modal Analysis (OMA)	Application of the response surface damage detection method in the case study of the Palazzo Geraci, structure that is continuum exposed to environmental conditions. Measures of dynamic response were recorded before and after retrofitting by filling the cracks with mortar. The aim of the study was to prove the metho to detect damage and a comparison between the different methods applied.
DAMAGE DETECTION IN EXISTING REINFORCED CONCRETE BUILDING USING FORCED VIBRATION TEST BASED ON MODE SHAPE DATA	(Tatar et al., 2017)	- Controlled excitation (shaker) - Operational Modal Analysis (OMA)	Damage detection of a full-scale nine-story reinforced concrete building which was damaged during an earthquake. In this case is investigated using forced vibration test. , performed on the structure before and after retrofitting with same sensor arrangement. It aims to confirm effectiveness of structure's rehabilitation and retrofit works
DAMAGE IDENTIFICATION IN REINFORCED CONCRETE STRUCTURES BY DYNAMIC STIFFNESS DETERMINATION	(Maeck et al., 2000b)	- Impulse excitation (instrumented hammer)	Here Maeck and others, propose an updating technique that uses only eigenfrequencies, as indicators of structural integrity. Study that was developed by testing two beams in a static and dynamic way. The static and dynamic set-up are represented. The aim is to identify degradation of stiffness, due to the cracking of the reinforced concrete, gives information on the position and severity of the damage.
DAMAGE IDENTIFICATION ON MASONRY STRUCTURES BASED ON VIBRATION SIGNATURES	(Ferreira, 2007)	- Operational Modal Analysis (OMA)	this thesis aims detect damage in masonry structures at an early stage by vibration measurements. With this objective there is presented the results of the testing of an arch and a masonry wall. Elements that were tested with no damage, and after being fractured. Modal analysis was performed at each damage stage, aiming at finding adequate correspondence between dynamic behavior and internal crack growth. The dynamic based methods allowed detecting and locating the damage in the specimens.
EARTHQUAKE DAMAGE DETECTION IN STRUCTURES AND EARLY WARNING	(M Todorovska & Trifunac, 2008b)		This paper reviews briefly the current methods, trends and outstanding issues in practical implementation of such systems, with emphasis on a new method based on detecting changes in wave travel times using impulse response functions. This method can be viewed as an intermediate scale method, bridging the gap between the NDT and global vibrational methods.
EVALUATION OF SEISMIC VULNERABILITY OF SANTA MARIA DEL MAR IN BARCELONA BY AN INTEGRATED APPROACH BASED ON	(Chellini et al., 2014)	- Operational Modal Analysis (OMA)	In this paper is a complete analysis of the survey techniques and procedure for vulnerability assessment of historical buildings. It is also presented the case of study of Santa Maria del Mar Church, monument that is a massive masonry construction in Barcelona. It goes from the process of historical investigation, numerical modeling, analysis of the loads that are affecting the building, and the

TERRESTRIAL LASER SCANNER AND FINITE ELEMENT MODELING			validation of the model with ambient vibration test. Finally, addresses the evaluation base on the FE model and the local mechanisms of collapse are determine.
EXPERIMENTAL INVESTIGATION OF INFLUENCES OF TRAFFIC LOAD ON THE CHURCH OF THE ASSUMPTION OF THE VIRGIN MARY IN STARÁ BOLESLAV	(Bayer et al., 2021a)	- Operational Modal Analysis (OMA)	This investigation of the influence of technical seismicity on the baroque Church of the Assumption of the Virgin Mary in Stará Boleslav. It presents the analysis of the data in order to obtain the vibration modes, the frequencies and amplitudes. Moreover, a statistical analysis was done to extrapolate the results to a future occurrence. The results are included in a plane model of the arch to relate the amplitudes with the concentration of stresses.
IN SITU STATIC AND DYNAMIC INVESTIGATIONS ON THE ‘‘TORRE GROSSA’’ MASONRY TOWER	(Bartoli et al., 2013)	- Flat jack tests - Operational Modal Analysis (OMA) - Coring tests	Presents the experimental campaign on ‘‘Torre Grossa’’ was composed of both in situ and laboratory tests. The in-situ tests (static and dynamic ones) were performed to assess the global structural behavior and the local masonry characteristics; the laboratory tests (crushing tests on cored samples) were performed to evaluate mechanical characteristics. A numerical model and a correlation of results between the experimental tests is presented.
INFLUENCE OF TECHNICAL SEISMICITY ON THE HISTORICAL BUILDING	(Urushadze et al., n.d.-b)	- Operational Modal Analysis (OMA)	Analyze and evaluate the effects of human induced vibrations on the Basilica of the Assumption of the Virgin Mary in Czech Republic, the response to stress caused by technical seismicity was evaluated using the effective vibration velocity (RMS) on the lowest level of the building at the so-called reference point.
Output-Only Modal Identification of Ancient L’Aquila City Hall and Civic Tower	(Cimellaro et al., 2012b)	- Operational Modal Analysis (OMA)	Evaluates Margherita Palace an ancient masonry city hall in L’Aquila, Italy that was damage during the L’Aquila earthquake in April 2009. In this report is presented the investigation of the testing campaigns was subjected to ambient vibration tests to determine its dynamic characteristics such as the natural frequencies, mode shapes, and damping ratios. It also presents the different methos for the treatment of the data.
MONITORING AND ASSESSING STRUCTURAL DAMAGE IN HISTORIC BUILDINGS	(Armesto et al., 2008)	- Photogrammetry - Shape parameters	Present a systematic procedure to evaluate the stability of structural damage by the use of digital photogrammetry, shape parameters and bootstrap as measuring techniques, for damage quantification.
Open-source digital technologies for low-cost monitoring of historical constructions	(Basto et al., 2017)	- Humiity sensors - Temperature sensors - Operational Modal Analysis (OMA)	Aims to present possibilities of using novel, low-cost platforms for the structural health monitoring of heritage structures in order to identify the suitable counterparts of the typical components of a continuous static monitoring system. There is presented the implementation in a case of study with different equipment and inverse arrangements to conclude in a system that in fact is a cost-efficient monitoring

QUANTIFYING THE VALUE OF SHM FOR EMERGENCY MANAGEMENT OF BRIDGES AT RISK FROM SEISMIC DAMAGE	(Omenzetter et al., 2017)	- Impulse excitation (instrumented hammer) - Controlled excitation (shaker) - Operational Modal Analysis (OMA)	This paper proposes a framework for quantifying the value of information that can be derived from a structural health monitoring (SHM) system installed on a bridge which may sustain damage in the mainshock of an earthquake and further damage in an aftershock. Furthermore, purpose a methodology to optimize the management of information from the SHM an how to update seismic risk by the information collected.
STIFFNESS CHANGES DUE TO STATIC LOADING OF A BRICK ARCH	(Bayer et al., n.d.)	- Impulse excitation (instrumented hammer)	A brick arch was loaded under laboratory conditions in three successive loading steps. The stiffness was evaluated in a non-destructive test using an impact hammer and only two accelerometers. The proposed identification technique based on known experimental modal analysis theory is tailored to stiffness evaluation of masonry vaults.

CHAPTER III METHODOLOGY

3.1 CASE STUDY: BASILICA OF THE ASSUMPTION OF THE VIRGIN MARY

The Basilica of the Assumption of the Virgin Mary, or the Bazilika Nanebevzetí Panny Marie in Czech Republic, has gained importance by being the oldest Marian pilgrimage site and one of the four church buildings in Stará Boleslav (Damašek, n.d.). The church is considered one of the most important monuments of early Baroque style in Bohemia. Built from 1613 to 1623 under direction of the imperial family, it is dedicated to the veneration of a medieval sacred relief of the Virgin Mary. Moreover, the importance of the church is also given by the decorations and artwork that includes one of the paintings of the famous Francesco Cozza. Two main phases or ornamentation processes are recognized. During the first stage, the major altar was donated by the Emperor while the other altars were provided by noble families of the time. The second stage refers to the restoration completed in 1670 after the interior was destroyed by the Swedish army in 1639-1640. (Vácha, n.d.)

Figure 3-1. Facade Basilica of the Assumption of Virgin Mary in Stará Boleslav.

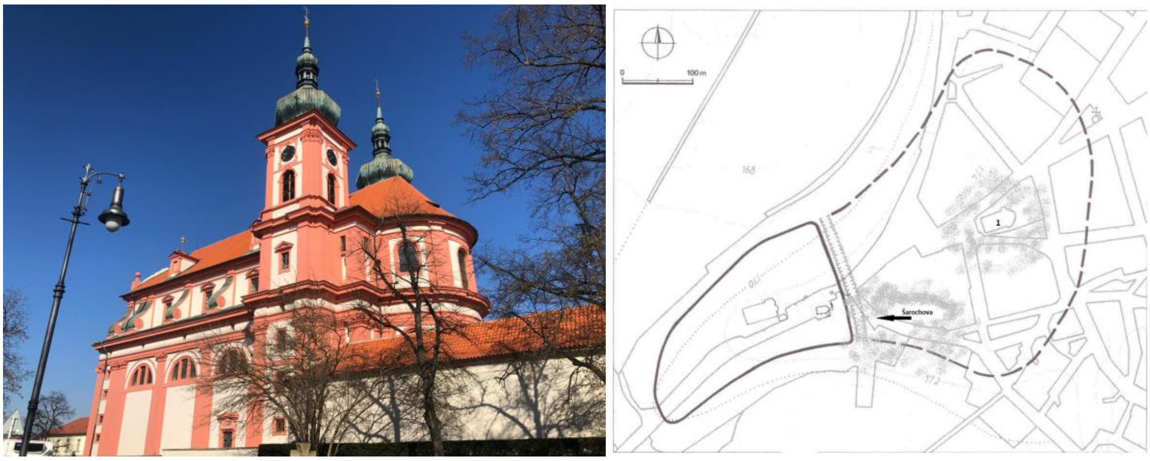


Figure 3-2. Overview of the back of the structure – Stara Boleslav fortification and acropolis (1) Basilica under study (Vácha, n.d.)

This sacred building is part of a complex that includes a terrace and a cloister see figure 3.2. (Urushadze et al., n.d.-a)

GEOMETRY OF THE STRUCTURE

The Church of the Assumption of the Virgin Mary is composed of a single nave and six vaulted side chapels that can be identified in figures 3.3 and 3.4 (Bayer et al., 2021b). The vaulted nave is made of brick and supported by pillars on each side. The layout of the church is rectangular with a semi-circular configuration where the main altar is located. The asset occupies an area of 22.2 meters wide by 48 meters long. The main nave has a height of 22 meters and a width of 13.8 meters (Urushadze et al., n.d.-a).

The section of the barrel vault without the thickness of the plaster is approximately 200 mm. The brick masonry wall is 1000 mm wide in the vault abutment. The pillars are tied between them with vault strips that form part of the barrel vault.

The pillars are 1.35 m x 4.3 m, including the external wall, with 4.3 m being the dimension perpendicular to the longitudinal axis of the church. The thickness of the external walls of the church is

1.2 meters and the height is the same as the pillars until the pilasters head. These pillars, with the external wall, create the lateral chapels. Moreover, there is a passage of 1.5 meters on the top of the vaults that is accessible from the towers. The church has two towers in the back, one on each side of the presbytery.

Figure 3-3. Cross section of the church (Bayer et al., 2021a)

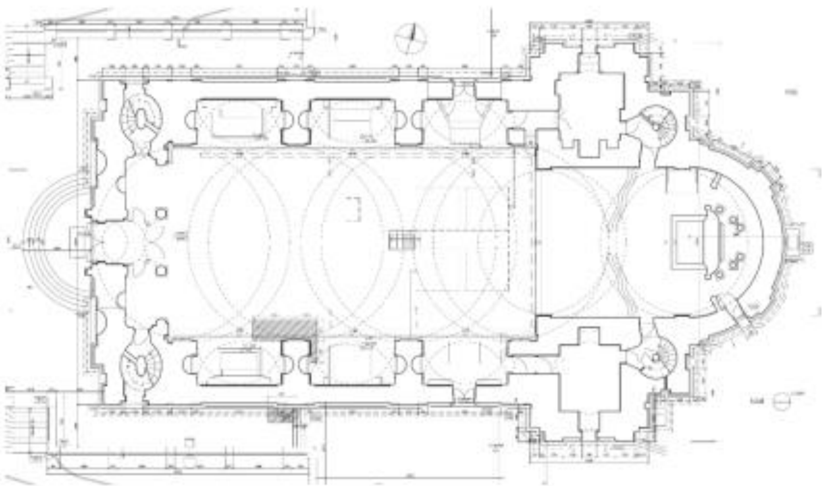


Figure 3-4. Plan view (Bayer et al., 2021a)

Figure 3-5. Space between the vault and the roof.

EXPERIMENTAL EQUIPMENT

According to the aims of the study, the sensors and equipment will be chosen and their location set. The selections can have consequences in the data treatment. Temperature, humidity and electrical protection are some of the parameters that can influence the measurements. Moreover, in order to verify the quality of the information collected, the cable to transfer the signals must be as short as possible. Additionally, to perform long monitoring campaigns, the instrumentation equipment must be easy to replace. (Rücker et al., 2006).

The sensors can be subdivided locally or globally, depending on the information that they provide. Local sensors are useful to provide information at the material level. On the other hand, global sensors will provide measurements that help to understand the behavior of the structure as a whole. Strain gauges, gratings, fibers, piezo film sensors, displacement sensors, hydrostatic leveling system, displacement sensors for relative vibrations, vibration wire strain gauges, vibration velocity sensors, vibration acceleration sensors are just some of the sensors that are most often used in SHM.

Equipment for long-term monitoring usually consists of a signal amplifier, an analogue antialiasing filter, a measurements data acquisition system, a computer for data management, processing and storage, a semiconductor for storage, an uninterruptible power supply, and a unit for remote data transmission (Rücker et al., 2006).

In the last campaign, 20 accelerometers were placed, seven of them to measure horizontal displacement in just one direction and placed on the top vault following the main axis, and the arch. The other thirteen accelerometers measure vibrations in horizontal and vertical directions.

For this campaign vibrations were measured using Wilcoxon Research Model 731A piezoelectric accelerometers, designed for low frequency vibration measurement on structures from 0.05 to 100 Hz, with high sensitivities of 10 V/g and noise characteristics of 0.5 µg RMS. The accelerometer measures reliably at temperatures of -10 °C to +65 °C. It has an integrated low-band filter, which can eliminate high frequencies caused by changes of acoustic pressure in the surrounding area. The accelerometers are connected to a Dewetron DEWE43 sixteen-channel computer with a 24-bit AD converter and simultaneous sampling of 200 kS/s. The input voltage can be adjusted to four ranges: ±10V, ±1V, ±100mV, and ±10mV.

Figure 3-6. Instrumentation of the arch.

3.2 PREVIOUS MEASUREMENTS AND MONITORING

EVALUATION PERIOD AND EVALUATED DATA

Due to the cracks that were located in different parts of the church, intervention was needed as it had been found that the vibrations on the top of the vault and the towers were exceeding the safe value of 0.2 mm/s in the standard *ČSN 730040.* Previous measurements were collected in the church in July 2018 on the crack vault and after the rehabilitation on the same place in April 2021. The test was based on dynamic measurements with environmental vibration.

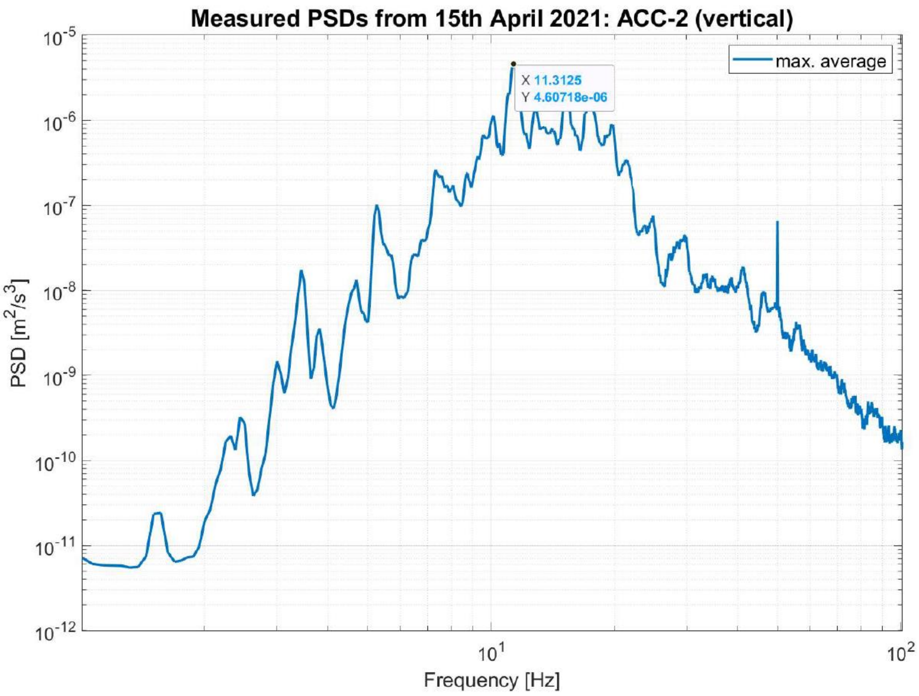


Figure 3-7. Measures on the arch in 2021

The traffic loads in these cases, as in the current study, were not measured. Furthermore, the differences between the fundamental frequencies can check the effectiveness of the intervention. (Bayer et al., 2021b)

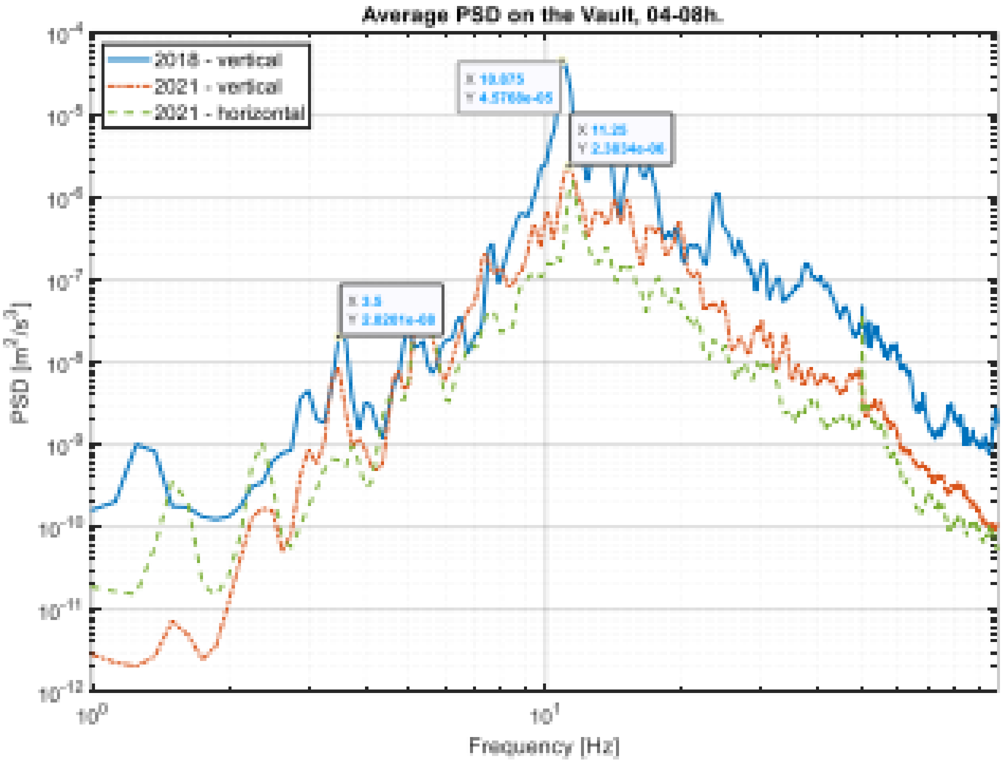


Figure 3-8. Average PSD in the vault. Before (blue) and after the interventions (orange and green).(Bayer et al., 2021b)

In order to assess the influence of the ambient and traffic induced vibrations on the main barrel vault over the nave after its repair, a new measurement scheme was launched. A cross section of the vault in the middle field was monitored for 12 hours in the measurement points.

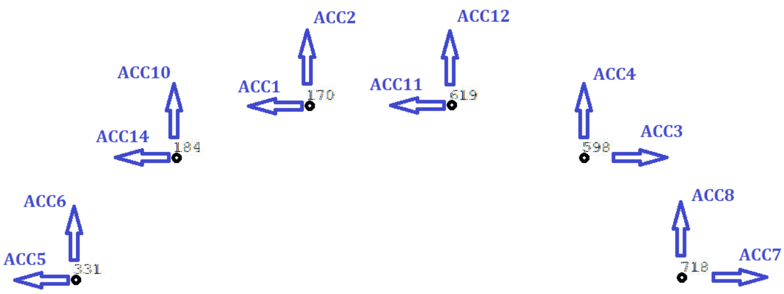


Figure 3-9. Position of accelerometers according to the nodes in the FE model

The frequencies for the evaluation are set to: 1.56 Hz, 2.38 Hz, 3.5 Hz, 3.81 Hz, 5.31 Hz, 9.25 Hz.

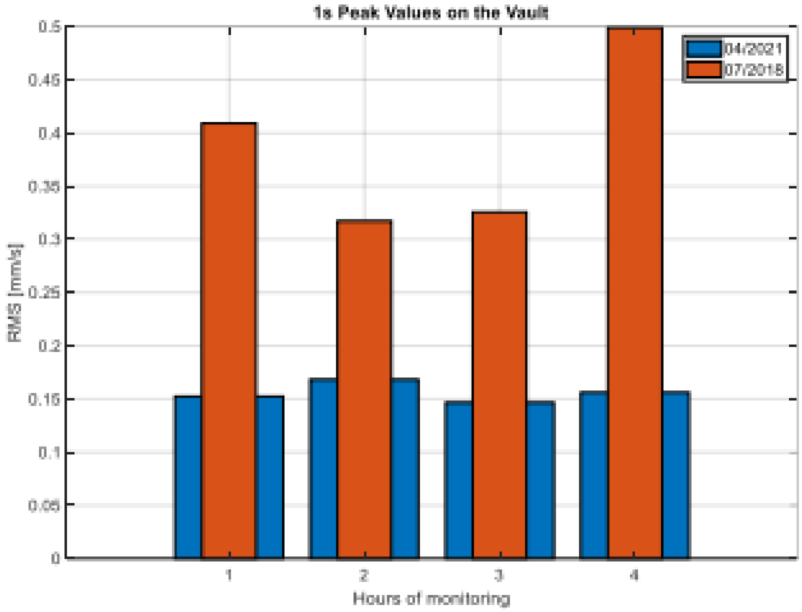
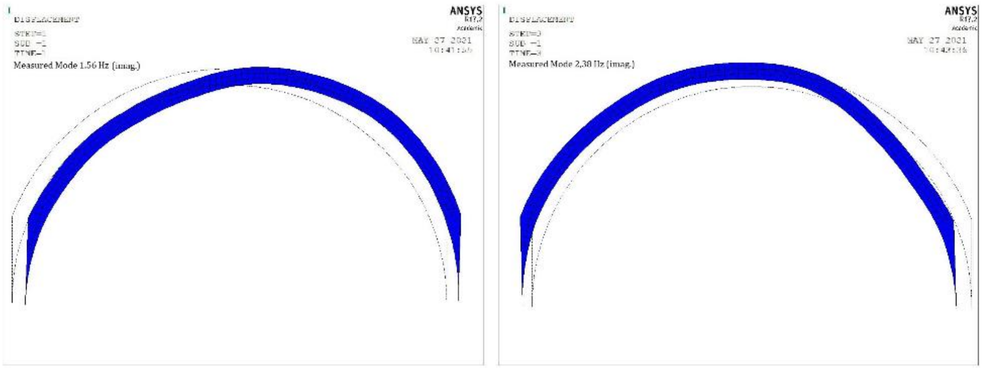


Figure 3-10. Peak velocities measured on the top of the vault.

The vibration shapes were evaluated at the frequency peaks chosen from the experimental data. As the values for the vibration modes are complex numbers, the figures that are shown below are done just with the imaginary part.



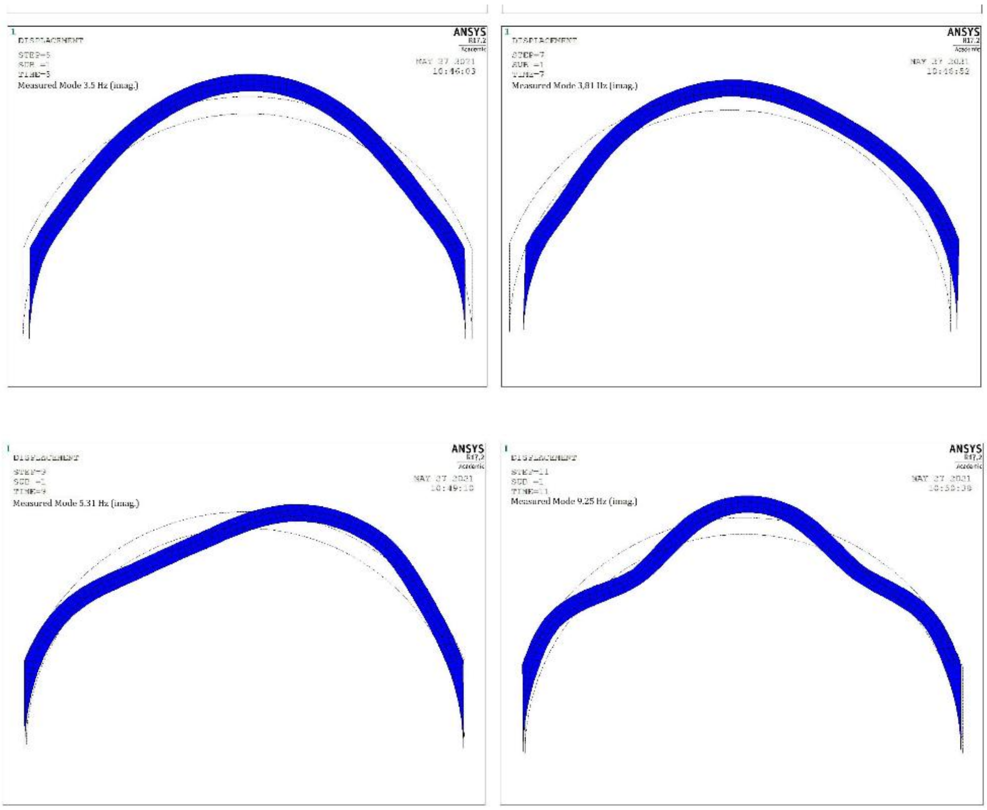


Figure 3-11. Vibration modes: 1.56 Hz, 2.38 Hz, 3.5 Hz, 3.81 Hz, 5.31 Hz, 9.25 Hz (top: left to right),

The vibration mode for 11.38 Hz deserves special attention because both components of the complex number (real and imaginary) show different behaviors as can be observed in the next figure.

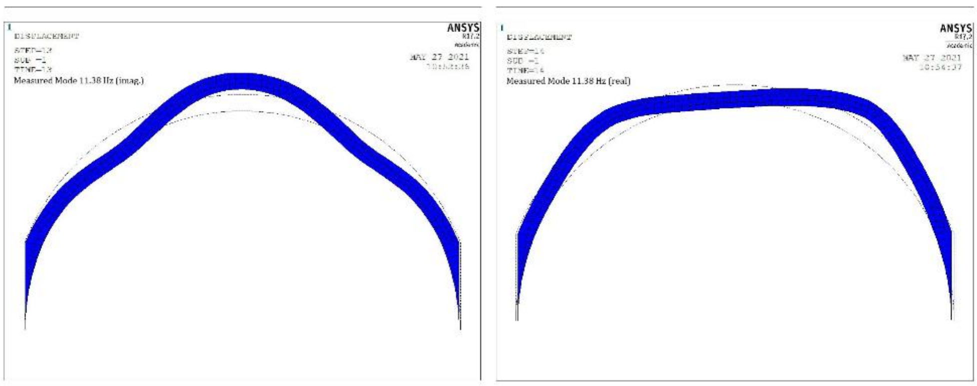


Figure 3-12. Vibration modes 11.38 Hz imag (left), 11.38 Hz real (right)

Using the Random Decrement Technique, together with low-pass filtering, free decay time records were evaluated for the natural frequencies 3.5 and 11.375 Hz (see Figures 5-6). Applying the analogy with the one degree of freedom system, the damping ratio of 0.01 was evaluated at the frequency of 3.5 Hz and 0.038 at the frequency of 11.375 Hz.

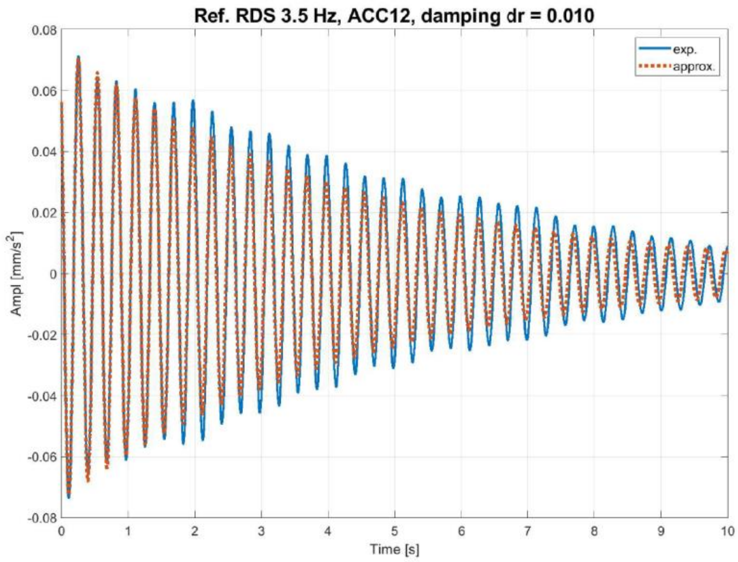


Figure 3-13 Damping from the decay curve at 3.5 Hz frequency

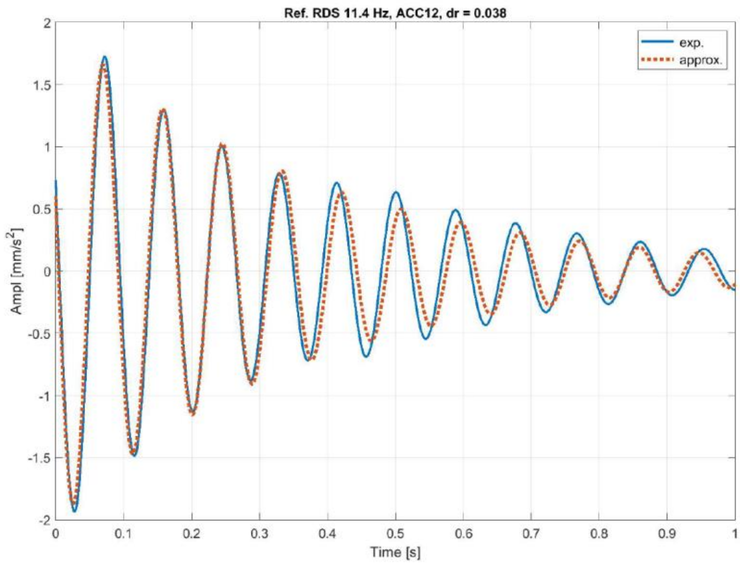


Figure 3-14. Damping from the decay curve at 11.38 Hz frequency

The previous study carried out in 2021 determined the maximum displacements for the frequency achieved experimentally at 11.38 Hz with the implementation of a FE model. The model has uncertainties due to the non-linearity of the material and the difficulties presented to include the effects in a plane model. The stress distribution is computed by loading the model with the displacements obtained experimentally, see figure 3.15

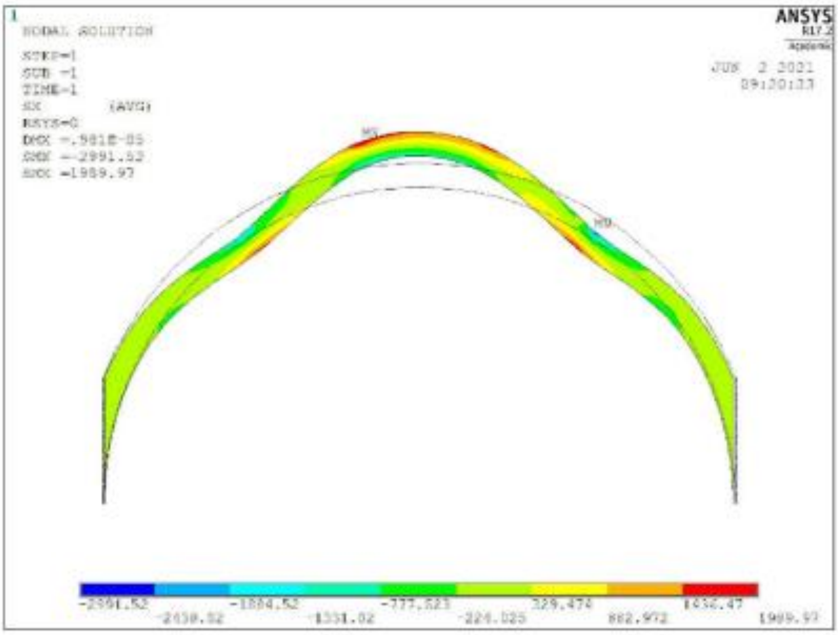


Figure 3-15. Maximum displacements at 11.38 Hz (Bayer et al., 2021b)

With the statistical distribution of the amplitudes for the mode at 11.4 Hz, the amplitude of 33 um and a tension stress of 7 kPa can be expected once in a year. In this study, it can be concluded that the structure does not reach these values in its fundamental mode. The maximum reached is 7.4 um and it corresponds to a stress in the vault of 1.4 kPa, both significantly lower than the limits described previously. Moreover, low pressure due to dead load in the midspan of the vault can develop the crack again for which is suggested a more detailed model.l (Bayer et al., 2021b)

3.3 MONITORING 2022

Information from the monitoring tools was collected from 13:00:00 on March 31st until 10:00:00 of April 21st. In total, three weeks of measurements were taken into account for the next report. Twenty accelerometers were placed in the longitudinal axis and in one of the arches and their position can be observed in the next figure. The measurements were taken in some points for vertical displacement and in others for both directions.

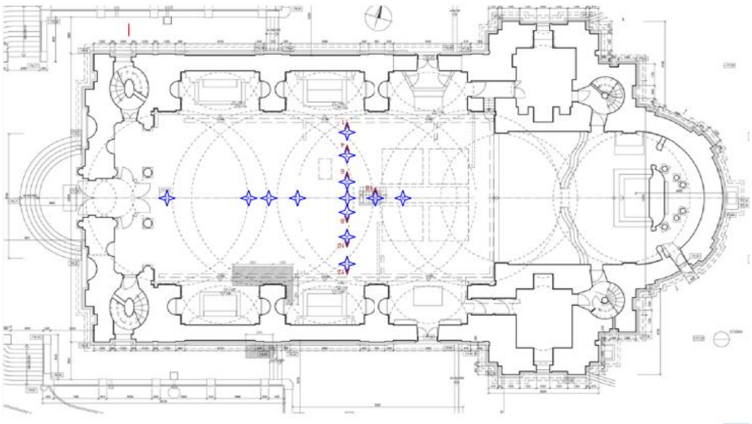


Figure 3-16 Position of the accelerometers, and type of tool used.

NUMBER OF SENSOR	*TYPE OF MEASURE*	*POSITION COORDINATES*		
		X [m]	Y [m]	Z [m]
1	Vertical	5.65	19.269	14.25
2	Horizontal	5.65	19.269	14.25
3	Vertical	3.68	21.028	14.25
4	Horizontal	3.68	21.028	14.25
5	Vertical	1.28	21.936	14.25
6	Horizontal	1.28	21.936	14.25
7	Vertical	-1.28	21.936	14.25
8	Horizontal	-1.28	21.936	14.25
9	Vertical	-3.68	21.028	14.25
10	Horizontal	-3.68	21.028	14.25
11	Vertical	-5.65	19.269	14.25
12	Horizontal	-5.65	19.269	14.25
13	Vertical	0	0	14.25
14	Vertical	0	0	12.64

15	Vertical	0	0	4.4
16	Vertical	0	0	8.4
17	Vertical	0	0	17.14
18	Horizontal	0	0	20.93
19	Vertical	0	0	20.93
20	Vertical	0	0	24.4

Table 3-1. description of sensors and position.

In order to compare the measurements with the data from 2021, the signal of the ACC-5 located in the same point is analysed.

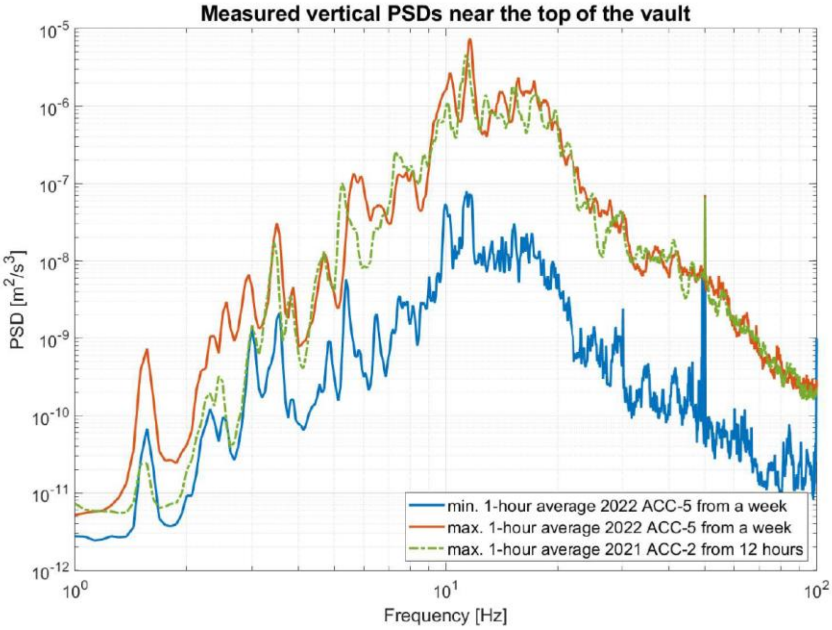


Figure 3-17. One-hour average PSDs near the top of the vault with the max. peak value

The values from both time lapses are really similar, but they are difficult to compare due to the difference in the duration of the monitoring. In 2021, the data collected corresponded to 12 hours. The difference then is not significant.T

3.4 MAXIMUM LEVEL OF VIBRATIONS

For the identification of the maximum amplitudes, the PSD of all the accelerometers was analyzed. The corresponding frequency was set on a range of 11.2 Hz to 11.8 Hz, which was the reason why the signal of the accelerometers presented in the next figure was done with the aim to identify the highest amplitude and the time at which this occurs. The next figure only takes into account the accelerometers located in the top of the vault where the maximum was previously found. The maximum amplitude at a frequency is identified as equal to 11.375 Hz.

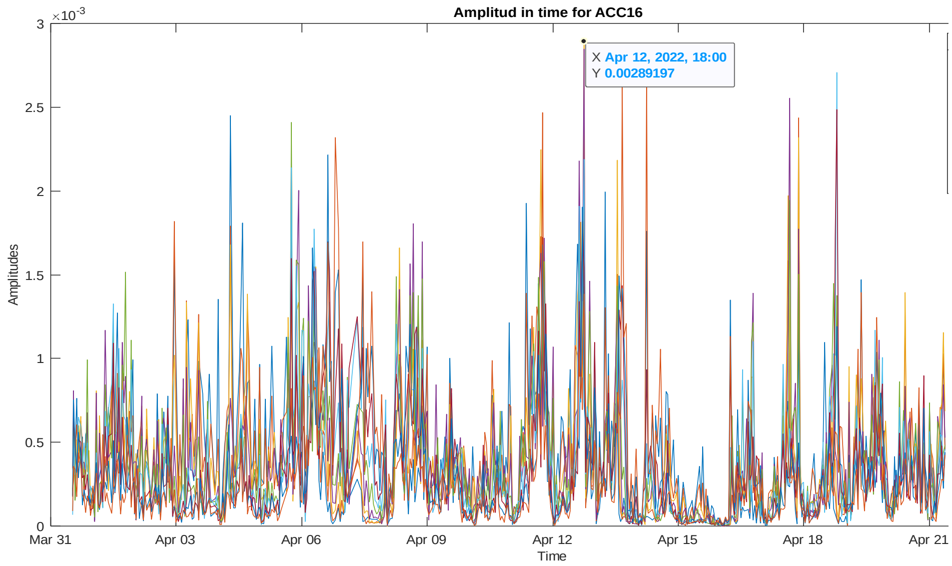


Figure 3-18. Amplitudes recorded in three weeks for the accelerometers on the top of the vault.

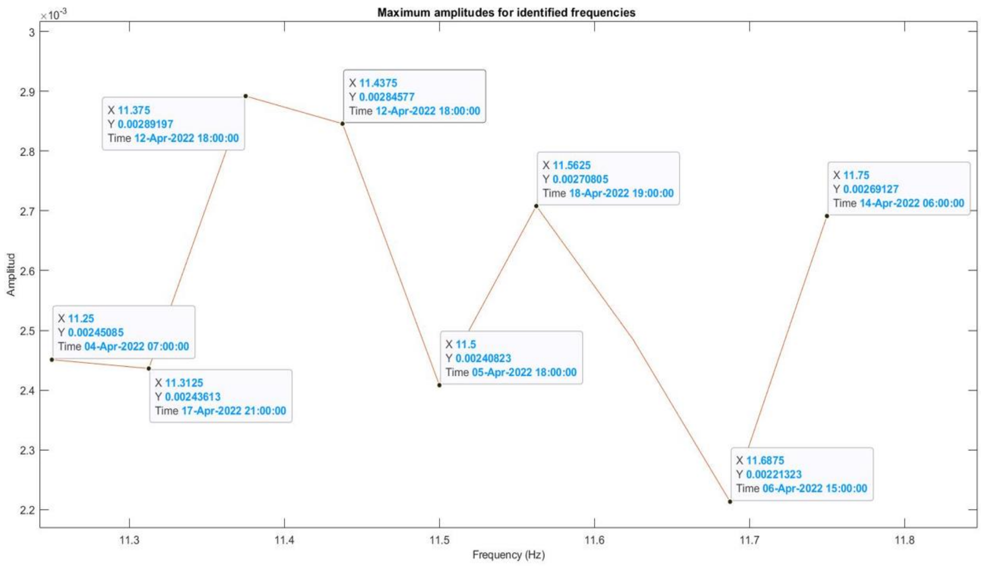


Figure 3-19. Maximum amplitudes for the frequencies between 11.2Hz an 11.8Hz.

Maximum amplitudes of vibration are at least 10 times higher than the average values. The maximum peak PSD in the next figure was evaluated from the selected 16 s time record which provides the maximum value from the whole three weeks.

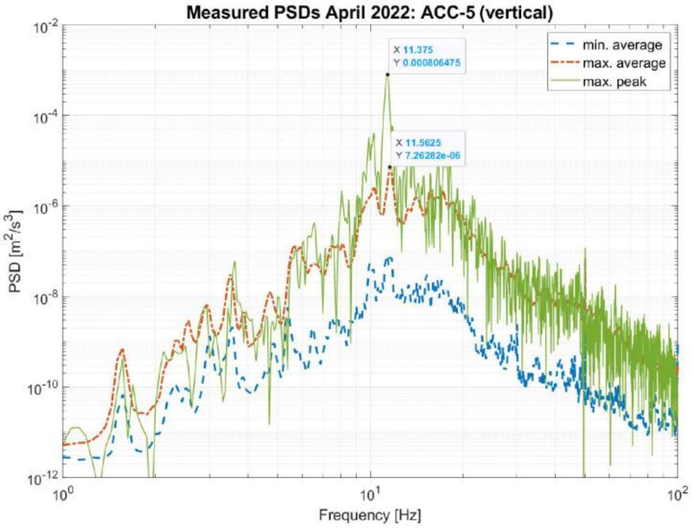


Figure 3-20. Comparison of one-hour average PSD with the maximum peak value

Amplification of the values obtained due to the discrepancies in the amplitudes obtained for maximum frequencies.

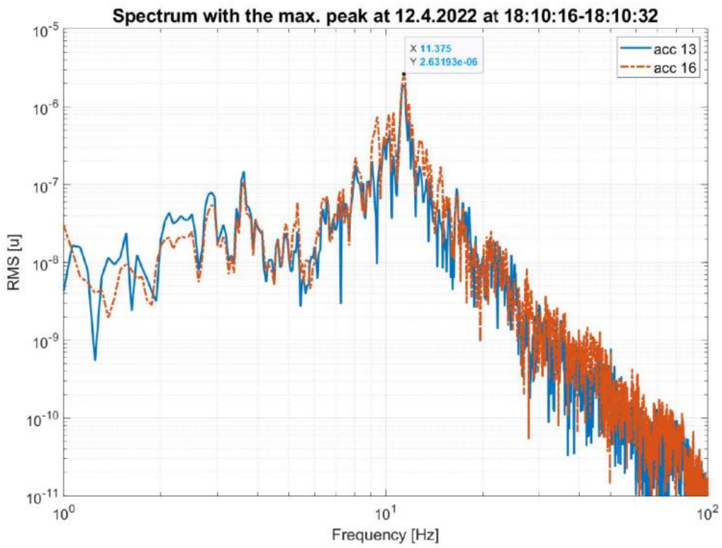


Figure 3-21. Spectra of the maximum peak values around 11 Hz scaled to RMS displacements.

The maximum peak around 11 Hz in the vertical direction was recorded at channel ACC-16, see also Figure 10. The maximum RMS amplitude in channel ACC-13 was 1.92 μm at 11.375 Hz.

A drop in frequency with increasing amplitude can be also observed and explained as a probable consequence of the non-linear behavior of masonry due to cracks or micro-cracks. This can be supported by the fact that the vibration mode at 11.5625 Hz evaluated from the average data corresponds well to the vibration shape at 11.375 Hz evaluated from the peak data.

The maximum-peak PSD spectra can be scaled to RMS displacements as shown in the previous figure. Nevertheless, it is still only an average value (from 16 s) and therefore, the maximum amplitudes within these 16 s can be higher than the frequency peaks. This is also the reason why the Rainflow Counting will be applied for evaluation of the maximum amplitudes.

CHAPTER IV RESULTS

4.1 VIBRATION MODES

MODAL IDENTIFICATION OF THE ARCH

The vibration mode in the traced cross section was evaluated for the moment where the vibrations were at the maximum level. In the next figure, the deformation of the arch loaded with the recorded deflections can be observed.

Figure 4-1. Vibration mode at 11.375 Hz (imaginary part)

The frequency of this mode did not present any significant changes since the last measurement. Any variation observed is within the uncertainty of the previous results, which also explains why the lower vibration modes are not presented.

MODAL IDENTIFICATION OF THE MAIN NAVE

The 2021 measurement provided the possibility to see the behavior of the vault along its main axes. The prevailing vibration modes in the vertical direction of the top line of the barrel vault are shown in the following figures. They were evaluated from the 1-hour averages. In the figures, the positions of the ribs in the main nave are also marked to understand the behavior of the elements and their relation to the deformation and stresses.

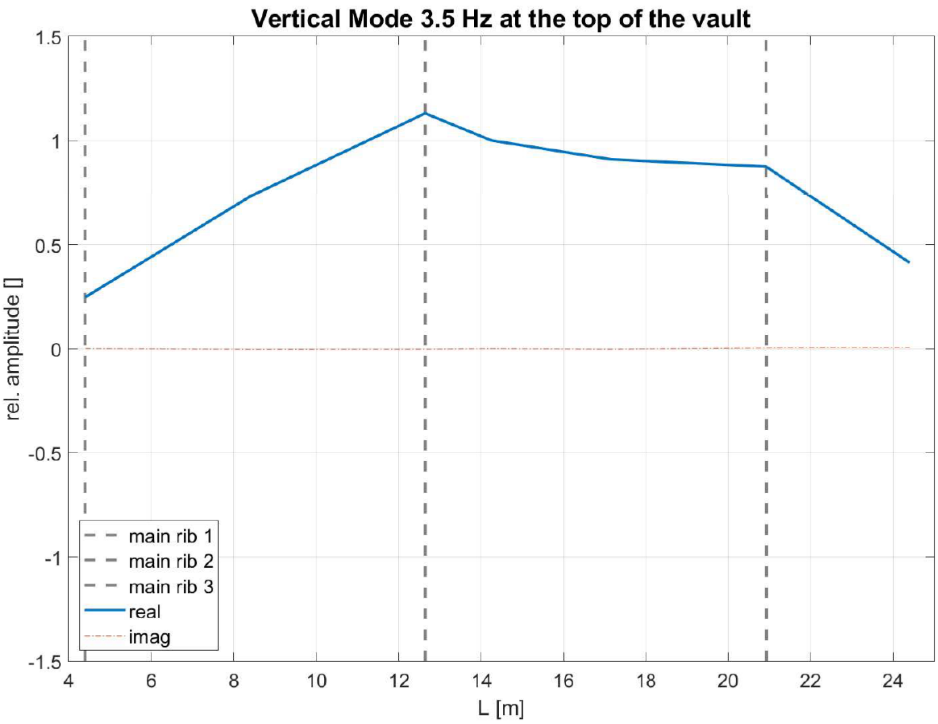


Figure 4-2. Vibration mode at 3.5 Hz along the vault top, vertical direction evaluated from 1-hour averages

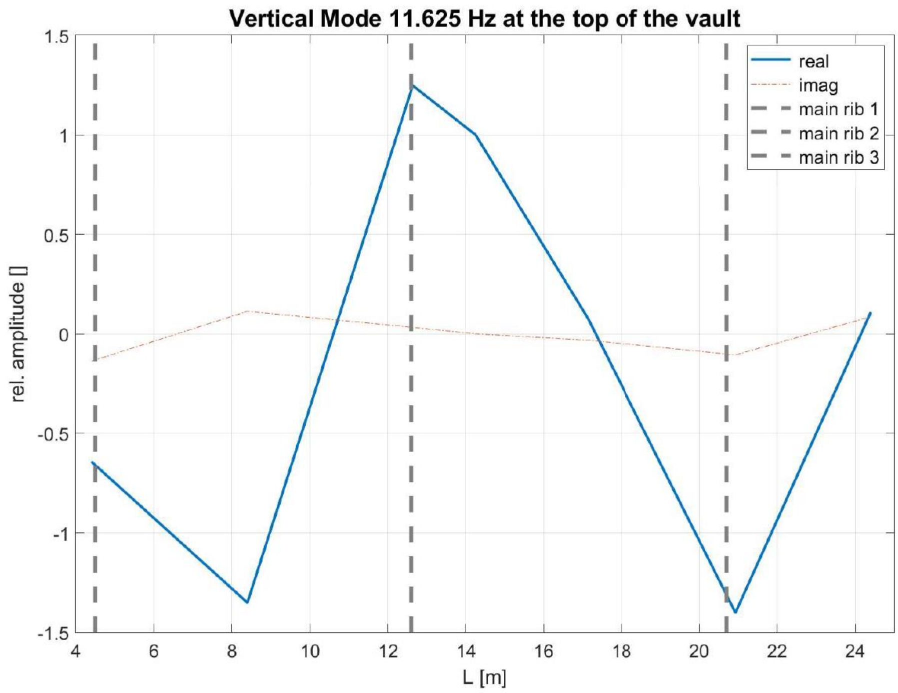


Figure 4-3. Vibration mode at 11.625 Hz along the vault top, vertical direction evaluated from 1-hour averages

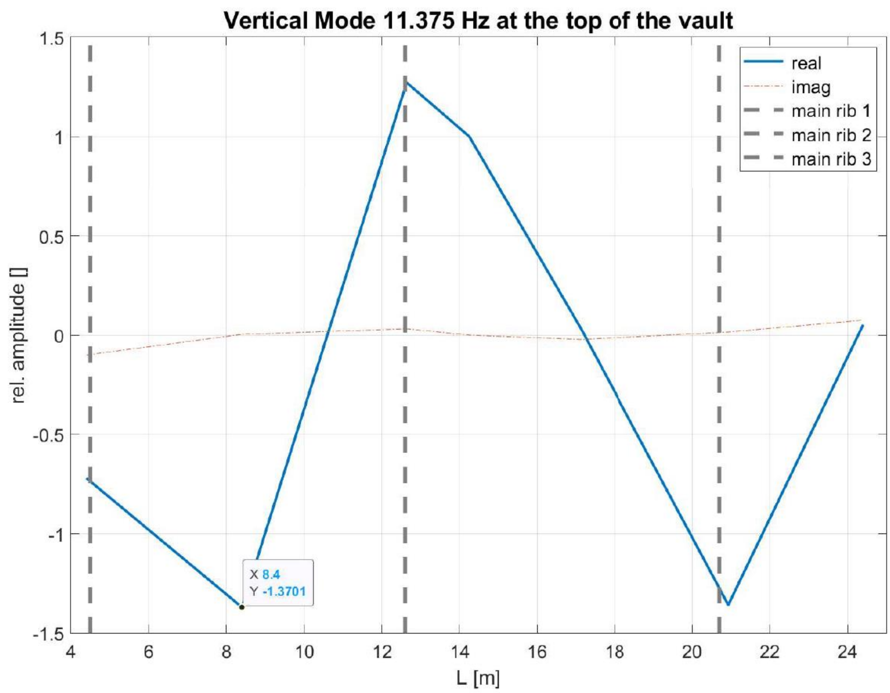


Figure 4-4 Vibration mode at 11.375Hz the vault top, vertical direction evaluated from 16s of max. reached level

Figures 13 and 14 are very similar to each other, confirming the above-mentioned fact that the frequencies are dropping down with increasing amplitudes.

Up to now, the maximum amplitudes were assumed to be in the traced cross section. However, Figure 14 shows that the amplitudes at the cross section 8.4 m are 1.37 times higher. Moreover, such a high amplitude can also be observed at the cross section 20.93 m, which is over the 3rd rib where the vault is also thicker and therefore likely to be more stressed.

4.2 RAINFLOW ANALYSIS

According to Amzallag et al. (1994)O, rainflow procedure is a cycle-counting method that allows the storage of service loads measurements in order to execute a fatigue analysis that can include fatigue prediction or allow a simulation testing.

Rainflow analysis is a useful tool to assess the expected fatigue life of a structure when it is submitted to a certain number of load cycles. For this analysis, a load statistical characterization in terms of quantification of the number of cycles, amplitudes and damage related to them is needed. Rainflow analysis is a useful tool when the structures are submitted to complex loads during its service life. (Benasciutti & Tovo, n.d.)

The application of this method requires a preliminary treatment of the information collected, the measurements are taken by an analogue signal and characterize a variable over time.

One of the advantages of this method is that it allows the numerical simulation of a large number of time histories based on the characterization of the random load by its spectral density without the need to do more testing campaigns. However, the main difficulty is the complex structure for the cycle extraction, the rainflow algorithm is a process described by the cycle distribution in time or in the frequency domain. (Benasciutti & Tovo, n.d.; Rychlik, 1987)

APLICATION OF RAINFLOW ANALYSIS

The Rainflow cycle counting method was used to estimate the maximum amplitudes of vibration in selected points in the narrow frequency band around 11.375 Hz (using the pass band range from 11.2 to 11.8 Hz).

Maximum values in selected points obtained from the counting are listed below:

Table 4-1 Maximum values in selected points obtained from the Rainflow counting, April 2022

RAINFLOW	***2A [M/S2]***	***A [M/S2]***	***A [UM]***
ACC_5 (ACC 2 / 2021)	0,033	0,0165	3,23
ACC_7 (ACC 12 / 2021)	0,039	0,0195	3,82
ACC_13	0,076	0,038	7,44
ACC_16	0,13	0,065	12,72

.

It is possible that a cycle counting in a wider frequency band could provide higher values. But looking at the spectra and knowing that a second distinct peak is at 3.5 Hz with amplitudes approximately 10 times lower then at 11.375 Hz, it can be assumed that the values in Table 1 are safe lower estimates of the real values.

STATISTICAL EVALUATION OF SELECTED PARAMETERS.

The statistical methods assume that the characteristics that affects the dynamic behavior of the system and its properties are totally contained in the measured response. Based on these assumptions the process of determination of damage will not need a model-based recognition method. The information used is collected by an output only test under normal conditions, and identification of damage will be spotted with changes in the distribution characteristics of the features. (Rücker et al., 2006)

A statistical analysis was carried out to recognize the maximum amplitudes and the number of cycles that this load was applied in the structure along the three weeks of measurements. The next graphs are an example of what has been done for all the accelerometers for the frequencies where the higher displacements were presented.

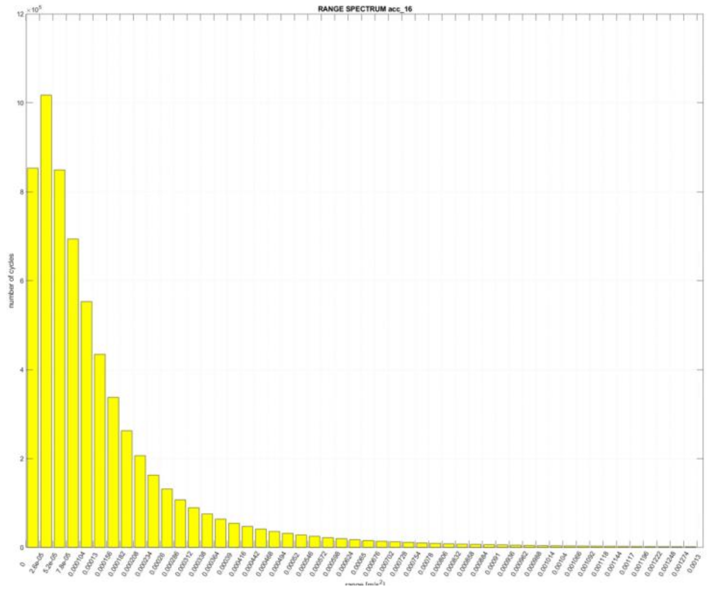


Figure 4-5. Amplitudes range of ACC16 and number of cycles for a frequency of 3.5Hz.

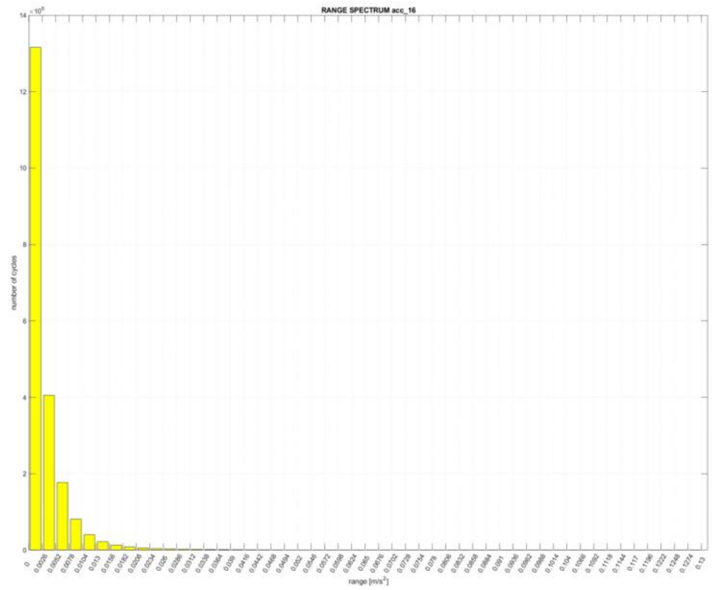


Figure 4-6. Amplitudes range of ACC16 and number of cycles for a frequency of 3.5Hz.

The maximum amplitudes occurred once in three weeks (3600*24*21=1.8144e6 s). The time of one period at 11.375 Hz takes 0.087912 s. Therefore, the probability of the maximum amplitude is 4.845. The rainflow counting was realized in 50 intervals from zero to the maximum level reached. Using the above mentioned scheme, we can calculate the probability for each of the intervals according to the following equation, where nc_i is number of cycles in the interval i.

$$p_i = \frac{nc_i}{11.375\text{Hz}} / 1.8144\text{e}6 \text{ s}$$

Plotting the probabilities on the x-axis, the probable number of cycles to reach an amplitude (reciprocal of p_i) and the central values of each interval on the Y axis, we obtain also a certain base for data extrapolation into the future 4-5.

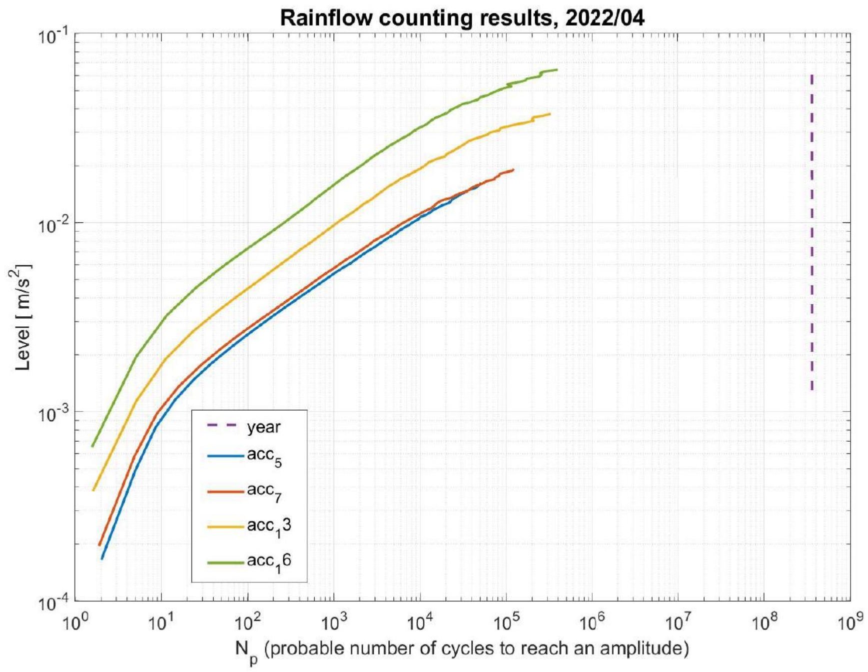


Figure 4-7 Results of Rainflow analysis for the selected transducers

However, the curves do not seem to have smooth higher derivations and therefore an extrapolation for longer future times may be rather uncertain. Reason why the attempt of extrapolating data for ACC-13 is showed in the next figure. This approach was possible due to the presence of one dominant peak in the spectra, which is quite a rare case. Otherwise, a mode superposition should be considered.

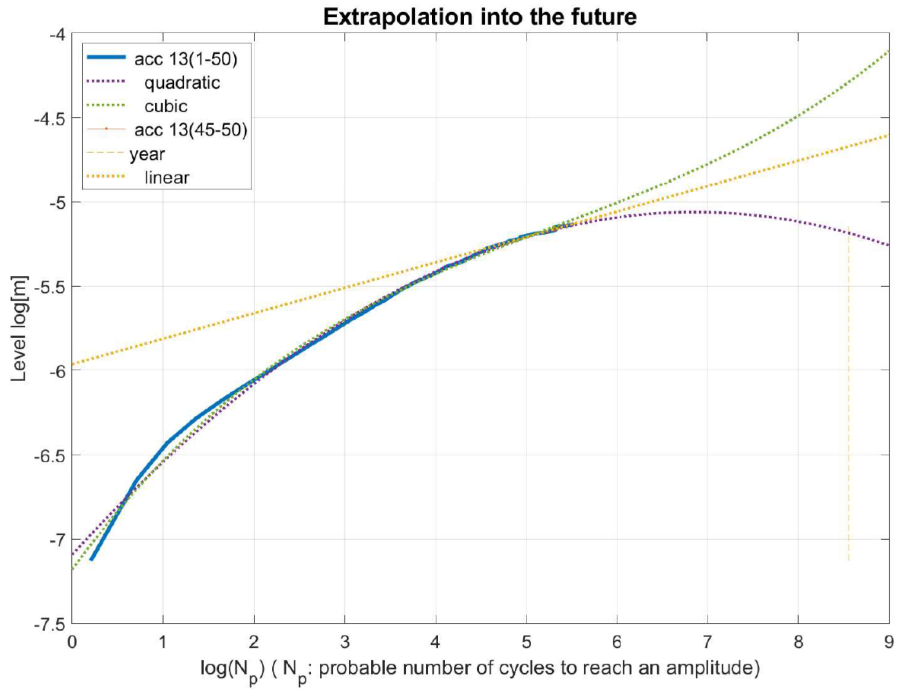


Figure 4-8. Extrapolation of data from acc_13 into the future

Nevertheless, a very rough estimate of one-year maximum for the amplitude at ACC-13 was done. The estimations also gave the number of cycles needed to reach the amplitude of 12.5 µm (10 – 15.8 µm).

4.3 STRESS ESTIMATION

The above estimated amplitudes were used for stress estimation using the plane FE-model applied in previous studies. The measured modes are scaled to the maximum amplitudes of ACC_13 presented in the previous table and the stress results are shown in figure 4.9. Moreover, it can be observed that the computed amplitudes at the top of the vault are lower than those measured in acc_13. The addition of a reference node on the top into the analysis leads to an unrealistic concentration of stresses at the top. On the other hand, a more severe change of curvatures at the top of the vault may be the consequence of cracks or micro cracks.

Taking into account a rather high uncertainty of this kind of semi-analytical stress estimation, the stresses in Figure 4--9 are an upper estimate for the stresses at the top of the vault in the traced section located in z=14.25m. Whit the previous estimation of deflection, a range can be set to 0.65-1.45 kPa for the whole monitoring period. If we will consider one-year amplitude, the stresses will approximately double.

Thus, the estimated stresses are lower than in the previous estimation from the year 2021. The difference in stress estimation is not a reflection of improved condition of the structure but rather of other less conservative assumptions made after the short 12-hour measurement in the year 2021.

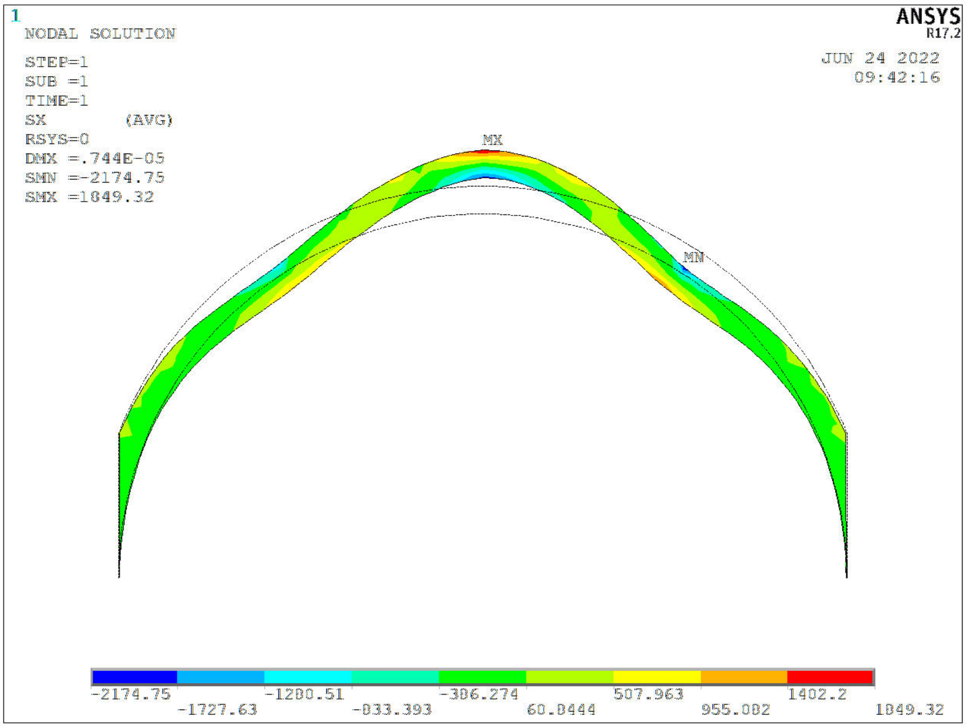


Figure 4-9. Vibration mode at 11.325 Hz scale for the maximum amplitude

New aspect in the estimation is the fact that the maximum amplitudes occur on the ribs of the barrel vault. They are approximately 1.71 times higher than the amplitudes in the reference position acc_13 according to the Table 2-3, and 1.37 times higher according to Mode Shapes. The distance of the neutral axis to the surface is 1.78 (0.25/0.14) times greater in the ribs than in the plain vault. If we assume that the vibration shape will have the same form in the traced cross section and in the ribs, then the stresses may be determined as 3 (1.78*1.71) times higher in the ribs than in the traced section which could make maximum stress amplitude of 9 kPa once a year.

CHAPTER V CONCLUSIONS AND DISCUSION

This project describes the experimental measurements of technical seismicity effects caused by environmental vibrations in the Basilica of the Assumption of the Virgin Mary in the Czech Republic. The measurements were taken for three weeks using 20 accelerometers placed in the main axis of the church and in one of the arches of the main nave. Significant changes were not found in relation with the measurements of 2021(after renovation) in terms of amplitudes, frequencies or in estimated stresses. Furthermore, Rainflow Counting was used to determine maximum occurred amplitudes and the amplitude counts for 50 intervals below the maximum amplitudes at each measured position.

The three-week monitoring period provided more reliable data and the expected maximum level in a year is now lower than the estimation from the year 2021 which was based on 12-hour monitoring. The assessment of the measurement indicates that the building is not subject to unacceptable mechanical vibrations.

In this case the effects of induced vibrations on the historical building were determined through non-destructive testing and monitoring, by the application of deformation recorded in the FE model giving stress results.

The vibration modes reveal that the first field of the barrel vault which is not strengthened by ribs supporting the dormitories has the largest vibration amplitudes, nearly equal amplitudes were also found at the transversal rib.

The vibration shape at 11.375 Hz has a complex shape along the main axis where the formation of three inflection points or knots can be seen. Further analysis is recommended to recognize the elements that are providing more stiffness and causing this mode shape. This could also lead to the recognition of some stress concentrations in the joints of the ribs where the knots are formed.

Extrapolation of data into the future is bound with such a large uncertainty that can be either due to the uncertain vibration shape outside of the measured section or due to the irregularities in the amplitude distribution obtained from the Rainflow Counting. Furthermore, these uncertainties could be avoid or decrease by a longer monitoring period or by the correlation with the numerical model.

The maximum estimated dynamic stresses in the barrel vault in the traced section (z = 14.25 m) can be expected in the range from approximately 0.65-1.45 kPa.

In fact, the amplitude values obtained in 2019 and 2022 are related to a peak frequency of 11.4 Hz. In 2019, the amplitude estimated was 33 μm under 7 kPa of load, values that are not comparable with the 1.92 μm obtained during this study. This is because the first value corresponds to an extrapolation of an occurrence in a year and is calculated from the measurements of the nearest sensors to the top of the vault and not in the center as in the last testing campaign. Furthermore, the values of 1.92 μm are obtained by RMS method where the average is chosen in data collected for 60 seconds. On the other hand, the values obtained by the rainflow analysis are comparable with the previous results and validate them.

Continuing with the monitoring will allow to increase the level of accuracy of the rainflow count and to detect any phenomena that can affect the building in time. If we refer to the values of frequency found, it is usually assumed that vibrations with higher frequencies do not cause as much damage as the ones lower than 10Hz, for which case the SHM will also be needed to keep track and measure the effects of the technical seismic loads.

Further monitoring of the Church could provide insight into fatigue of the masonry caused by low level vibrations. It can also provide a timely warning in case of sudden condition deterioration.

As part of the monitoring sensor of temperature was installed, values that can be useful to relate the behavior of the structure with the environmental effects for further analysis. As well the study of the traffic in the adjacent road can reveal the source of extreme amplitudes.

Due to the time designated for this project, it was not possible to include further results, such as the correlation of the FE model which is important to predict the future behavior of the structure and evaluation of damage.

The methodology proposed, is applicable for other historical buildings where information of structural health monitoring can be collected and processed; Being the rainflow counting method a important tool to determine the concentration of stresses with the identification of the maximum amplitudes.

For some of modal testing applications, the bigger problems are concerned with the correct determination of forces. Moreover, in the case of the uses for the sub structure systems, the determination of the methods of coupling will play an important role to have reliable results.

As a reminder, it needs to be said that no single test or analysis procedure is the ‘best’ for all the cases of study. A previous analysis and delimitation of the pursued aims of the study will ensure the most appropriate and effective method and technique to achieve them.

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