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VIBRATION MEASUREMENT IN THE DEGRADATION STUDY OF BUILDING CONSTRUCTION MATERIALS

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ABSTRACT

Brick objects are subject to large dynamic loads clearly reflected by generated vibration processes. The vibrations may affect the state of serviceability of structures by lowering the comfort of persons working there, as well as possibly reaching a level hazardous to the safety of the structures. The effect of vibrations on the structure is mainly manifested by additional stresses in a given cross-section, which are summed up with those resulting from static loads. The dynamic loads may cause damaging effects in buildings of various structural types or even lead to their destruction. The article describes a series of original analyses of the process of destruction of selected masonry objects using the experimental modal analysis. The research was conducted to improve the quality assessment of building structures in terms of the technical condition of masonry structures and meeting safety standards.

Keywords: modal analysis, natural vibration frequency, stabilisation diagram, structural vibrations

INTRODUCTION

Modern building constructions and the production of low-noise machines and devices are associated with a high level of precision in their manufacture and the appropriate selection of materials, which greatly affect their quality, reliability and durability (Stępniewski, Uhl & Staszewski, 2013).

When studying real systems (structures, buildings, machines, equipment), the main problem is determining the energy stored, dissipated and transmitted by certain system elements. Knowledge of dimensions can be used to assess material costs, fatigue, diagnostic checks and noise level predictions, and also aids in the design of system components – e.g., vibration isolation (Allemang & Phillips, 2004).

The development of measurement methods, especially energy measurement methods, has greatly expanded the possibilities for studying sound radiation from buildings and made it possible to calculate the sound power radiated into the far field based on near-field measurements. Quantitative and qualitative research methods for the propagation of vibro-acoustic energy in spaces with complex boundary regions have been developed. It is related to the quantitative assessment of the vibro-acoustic energy stored in structural elements and the energy radiated from the elements and transmitted in different ways (Cempel, 1994).

Modern architectural structural dynamics uses various research tools in the field of state determination, such as the boundary element method, the finite element method and modal analysis methods, to better understand the behaviour of complex structures through modelling and investigation of state changes, guide their optimisation during the design process and assess their current – often dangerous – conditions (Cempel, 2003).

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Considering the need to improve research methods dealing with the quality of brick structures in order to assess the condition and safety factor of brick structures (see Polish standard PN-B-03002 by Polski Komitet Normalizacyjny [PKN], 2007), in this work, the author attempted to develop research methods by using the experimental modal analysis method to evaluate the failure quality of selected building structures.

There is a need for improved methods for studying the dynamic behaviour of structures, especially those subjected to large dynamic loads. New materials and technical methods are introduced into construction projects, as well as novel constructive solutions, which allow for increased productivity and product quality, but are accompanied by huge, often dangerous, dynamic loads. The problem is receiving more and more attention (Stępniewski et al., 2013).

Vibration – the process that accompanies every movement – in structural engineering can be classified into the categories of harmful, beneficial, or informative vibrations. Vibration is the primary process, the (secondary) effect of which is an acoustic signal in the form of longitudinal sound waves. Vibration and noise processes form the basis of the scientific research field 'vibro-acoustic'. Modern architecture is accompanied by vibro-acoustic phenomena that endanger humans, the environment and their products. Trends in contemporary engineering and technology, coupled with ever-increasing dynamic loads, speeds, weights and minimisation of materials, make an increase in vibration and noise inevitable. These trends, together with the massive application of technological means, pose risks to humans, nature and the technological environment (Uhl, 1997).

In most cases encountered in practice, the analysis of dynamic characteristics is carried out based on the analysis of the behaviour of the structural model. The quality of the analysis depends on the credibility of the model, which is measured by the conformity of the behaviour of the object and the model, both subject to the same type of perturbation. Structural models can be created during analytical transformations used to describe system dynamics or can be based on the results of experiments performed on real objects (Wiliams, Crowley & Vold, 1985).

The analysis of the dynamic properties of structures is mainly carried out by studying the behaviour of a dynamic model of a given structure, which can be done by using analytical descriptions of quantities characterising the dynamics of the system or directly applied to practical experimental methods. Objects are implemented (Żółtowski, 2014).

New tools in this field of research relate to the possible application of modal analysis methods and modern methods of extraction and processing of vibration methods to assess the quality of masonry structures and elements, which is the subject of this work. In practice, they can better understand the behaviour of complex structures, optimise them during design and assess dangerous states. The latter area includes references to the studied problem of finding criteria for the assessment of the state of degradation of old and new brick wall structures and elements, usually those for which the state of failure and the value of the factor of safety are unknown.

Modal analysis is widely used in aeronautical and civil engineering to investigate degradation states and failure locations, modify the dynamics of structures under test, describe and update analysis models and monitor structural vibrations. The following terms can be found in specialised literature: modal analysis, experimental modal analysis and operational modal analysis (Żółtowski & Żółtowski, 2014). Most practical applications of modal analysis require multi-channel experiments and complex calculations associated with processing measured signals and estimating model parameters. The possible applications seen in this way allow distinguishing the following types of modal analysis (Żółtowski & Martinod, 2016):

- theoretical – requires solving the eigenvalue problem for a given structural model of an investigated object;
- experimental – requires controlling the identification experiment during which the object's motion (e.g., vibration) is excited, and measurements of excitation and response are performed in many measuring points;
- operational – based on an experiment carried out in real conditions, during which only the system's response is measured, and the object's motion results from real operational excitations.

SCOPE OF THE EXPERIMENT

The experiment for identifying the destruction state of the studied wall elements is the basic source of information – and on its basis, the value of measures and the structure of the model can be established. The quality of the received model is influenced by the quality of the experimental research findings on the one hand, and the identified model's structure on the other. The modal analysis experiment can be divided into the following stages:

1. Planning:
   - the choice of the way of extorting trembling on the studied elements and the points of application;
   - the choice of points for measuring the trembling and the measuring apparatus;
   - the choice of suitable measuring equipment;
   - the choice of the modelling arrangement (the limitation of the number of degrees of liberty).
2. Calibration of the measuring track.
3. Acquisition and processing of the results.

The studied wall element shows the trembling force of signal extortion proportional to the state of the destruction. The extortion signal and the answer were used for further delimitation of the FRF and the stabilisation diagram.

The equipment necessary for the execution of the experiment of modal analysis consists of the following elements:

- the arrangement for measuring the extortion of movement and the answer;
- the arrangement of signals (the preliminary processing);
- the arrangement for processing and assembling the signals;
- the arrangement for generating the extorting signal;
- the arrangement for arousing the trembling.

As far as service solutions are concerned, the use of signal analysers is the simplest machine but also the most modern, and it offers the greatest possibility of a workstation-specific measurement interface. The basic operation a signal analyser can perform is conventional analogue-to-digital processing, which allows the use of digital techniques when processing modal analysis signals.

In a modal study, it is not important which kinematic quantities are measured. In practice, however, displacement measurements occur in the low-frequency range, while acceleration measurements occur in the high-frequency range. Velocity measurements in structural dynamics studies are known to be best in terms of the RMS value of the shaking velocity obtained by measuring the kinetic energy of the shaking component. However, the sensors that measure displacement and velocity are heavy compared to the materials under study and can affect their behaviour.

The sensors that measure acceleration have a much smaller mass and therefore do not affect the movement of the component. An added benefit of using sensors is that they get a combined acceleration signal of velocity and jerk displacement. Reverse operation depends on differential jitter, which can lead to large errors – especially at higher frequencies. The sensor has a natural resonance, which limits the frequency of use.

The choice of where to install the sensor is crucial as it can affect the results of the modal measurements. Sensors should be mounted so that they do not affect equipment vibrations and should also be fixed at characteristic points of the structure.

Experimental modal analysis requires accurate laboratory conditions for investigation. The model must have known Berg. Extortion can evade these, which they inflict on objects during normal exploitation. When conducting experiments, we may encounter difficulties that correspond to the reality of the conditions onshore: immobilising the research subjects. In the case of large models, performing this experiment is time-consuming.

This paper presents the results of a study of the differentiated states of brick structures obtained by applying experimental modal analysis. For this purpose, the LMS SCADAS Recorder – a device combining the functions of an analyser and a classic recorder, and the Simcenter Testlab (LMS Test.Lab) software for performing the tests and visualising the results were used.

VIBRATIONS IN THE DESCRIPTION OF STRUCTURES

Vibro-acoustics is a domain of science which deals with any vibration, acoustic and pulsation processes occurring in nature, building engineering, technology, machines, devices, communication and transport means (i.e., in the environment). Among the tasks of vibro-acoustics, the following may be rated (Żółtowski, Łukasiewicz & Kałaczyński, 2012):

– the identification of vibro-acoustic energy sources, which consists of location-particular sources within the structure of an object, machine or environment, the determination of their characteristics and mutual relationship, the determination of vibro-acoustic power as well as the character of vibration and sound generation;
– the elaboration of vibro-acoustic energy propagation paths in real structures and environments (buildings, machines, objects, etc.), the theory of energy transmission and transformation, passive and active control means for phenomena, methods for analysing and testing phenomena at the border area between wave and discrete approach;
– the elaboration of control methods for vibro-acoustic energy (emission, propagation) in building structures, machines and environments, and also the elaboration of methods for steering the phenomena is associated with active methods which are presently under development worldwide;
– the use of vibro-acoustic signals for the purposes of technical state diagnostics as they constitute a good carrier of information on the state of an object's destruction as well as the technological process under-way (vibro-acoustic diagnostics);
– the vibro-acoustic synthesis of objects, performed to obtain optimum vibro-acoustic activity (structural, kinematic, dynamic), which covers the synthesis of parameters used in active methods for vibration and noise mitigation, as well as the structural, kinematic and dynamic synthesis of objects and machines;
– the active applications of vibro-acoustic energy to realising various technological processes, beginning from ultrasonic welding and cleaning, transport of materials and machine elements along technological lines, consolidation of moulding sands, shaking out and cleaning castings, ending at the consolidation of soils and different types of concrete.

The vibro-acoustic process may be presented as:

– generation of time-varying forces acting on a structure and its environment;
– propagation and transformation of energy in different environment structures;
– sound radiation through material elements of the environment.

In the analysis of vibro-acoustic processes, the following is taken into account:

– time-space distribution of run of energy coming from a (primary) source;
– response of a system (structure, liquid) as well as energy transmission through propagating media;
– the mutual relationship between sources.

The concept of measurement refers to the process of acquiring and transforming information about what is being measured in order to obtain quantitative results in a form most accessible to the human sensory organs by comparison with units of measurement, converting it into space or time (recording), mathematical processing or go to the application.

To make such measurements (Żółtowski & Żółtowski, 2014) are necessary:

– determining the time course of vibrations and their parameters to determine vibration types, characteristic sizes and perform detailed analysis; determining of time runs of vibrations and their parameters to determine the kinds of vibrations, their characteristic quantities and to perform a detailed analysis;
– finding vibration sources and places of their occurrence;
– determining characteristic features of systems (e.g., determining loads during vibrations and their dependence on an object's parameters, its shape, dimensions, material properties, etc.);
– minimising vibrations harmful to the reliable operation of devices and their human operators;
– determining harmfulness level of occurring vibrations and implementing preventive measures.

In practice, vibration signals are more commonly used than noise signals because of their ease of transmission and accurate measurement (Żółtowski & Żółtowski, 2014).

The system vibration in which the equilibrium state of an object is disturbed and moves under the action of elastic force, gravity or friction is called free vibration. In a system with one-degree of freedom (1-DOF), the disturbance of the equilibrium state is characterised by initial conditions: initial position (x_0) and initial velocity (v_0). If a system consists of 1-DOF (Fig. 1) – i.e., single mass (m), and linear properties of elasticity (k) and damping (c), with a harmonic excitation force $F(t)$ acting on it – then its equation of motion is expressed by the following formula:

$$m\overset{**}{x} + c\overset{*}{x} + kx = F(t), \tag{1}$$

which represents the equation of harmonic vibrations or harmonic oscillator vibrations.

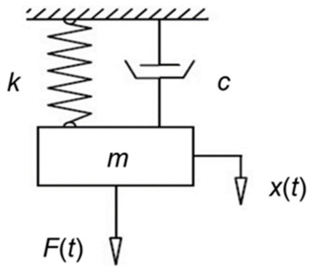

Fig. 1. One-degree-of-freedom system to perform translation motion

Source: own work.

As a result of it, natural vibration of the 1-DOF system is entirely determined by natural frequency of vibration. The amplitude of the vibration depends on initial conditions but natural frequencies and the vibration period do not depend on them. The solution of the equation (i.e., translation) takes the following form:

$$x = A\sin(\omega_0 t + \phi). \tag{2}$$

By differentiating this equation, the vibration velocity is obtained:

$$\overset{*}{x} = A\omega_0 \cos(\omega_0 t + \phi), \tag{3}$$

which is also a periodical function of time, of the same period as that of translation. By differentiating the velocity equation, the value of vibration acceleration is obtained:

$$\overset{**}{x} = -A\omega_0^2 \sin(\omega_0 t + \phi) = -\omega_0{}^2 x. \tag{4}$$

It is a periodical function of time, the same period as translation and velocity. Acceleration is proportional to translation and directed against it (i.e., it always is pointing position of equilibrium).

The parameters a, v and x are those of the vibration process, which proves that the vibrations properly describe the state of the structure.

In the low-frequency range, building structures can be modelled by using discrete systems of a few DOFs – and rather often – a 1-DOF system. In contrast to continuous one, the discrete system is characterised by point distribution of mass, stiffness and damping and dimensions of the elements do not play any role. The number of DOFs determines the number of independent coordinates which should be introduced to get an unambiguous description of the system's motion (the number of DOFs is equal to the number of mass elements in the system in question). In practice, the system presented in Figure 1 can model:

- the building machine of mass (m), seated on shock absorbers (k, c) and fastened to a big mass foundation;
- the work machine of mass (m), seated on shock absorbers (k, c) and moving along an even road;
- the high building structure (high chimney, mast) under wind action.

The output signal received at any structural point is the weighted sum of the responses to all elementary events (t, w, r) that occur at some point in the dynamical system with the momentum transfer function $h(t, \theta, r)$. These effects add up with additional transformations along different reference axes, and changes in the signal reception point (r) are also associated with changes in transmittance.

The vibration signal transmission model through the test structure or wall element is actually described by the FRF, which is determined by the experimental modal analysis in the form of the ratio of the vibration excitation force to the amplitude of the vibration acceleration at the output. Permeability $H(f)$ is defined as the response to the excitation ratio, which is the reciprocal of the FRF. The indicated properties of the elaborated model of signal transition through tested materials were further used for assessing changes in the degree of degradation of structures or brick wall elements during the testing transition of vibration signals through various structures of brick wall elements and segments.

A modal analysis is widely applied for removing damages resulting from vibrations, modifying structure dynamics, updating analytical models or state control, and is also used for monitoring vibrations in the aircraft industry and civil engineering (Stępniewski et al., 2013).

$$\varpi = [\varpi_1,\ \varpi_2,\ \ldots,\ \varpi_n]. \tag{5}$$

The theoretical modal analysis is mainly used in the design process (i.e., when it is not possible to perform tests on objects). The traditional experimental modal analysis (EAM) makes use of input (excitation) to output (response) relation, and it is measured to assess modal parameters consisting of modal frequencies and damping. However, the traditional EAM has some limitations, such as:

– in the traditional EAM, artificial excitation is used to measure vibration frequencies;
– the traditional EAM is usually performed in laboratory conditions.

However, in many cases, a real state of degradation may greatly differ from those observed in a laboratory environment. In experimental modal analysis, the identification experiment consists of exciting the object's vibrations at simultaneous measuring excitation forces, and the system's response is usually in the form of vibration acceleration amplitude.

RESULTS AND DISCUSSION

The measurement equipment for measuring the frequency response function is used to measure the wave shape and the response system and determine the most commonly used functions. Using Simcenter Testlab software (Fig. 2), you can easily perform modal analysis on brick elements and other building structures.

A fit and a damaged brick were measured from a large group of building materials to compare their fitness. Figure 3 shows the results obtained after performing measurements on axis Y because, in brick walls, compressive strength can be most destructive.

For a better visualisation of the results of the investigation, the results are shown separately (Fig. 4)

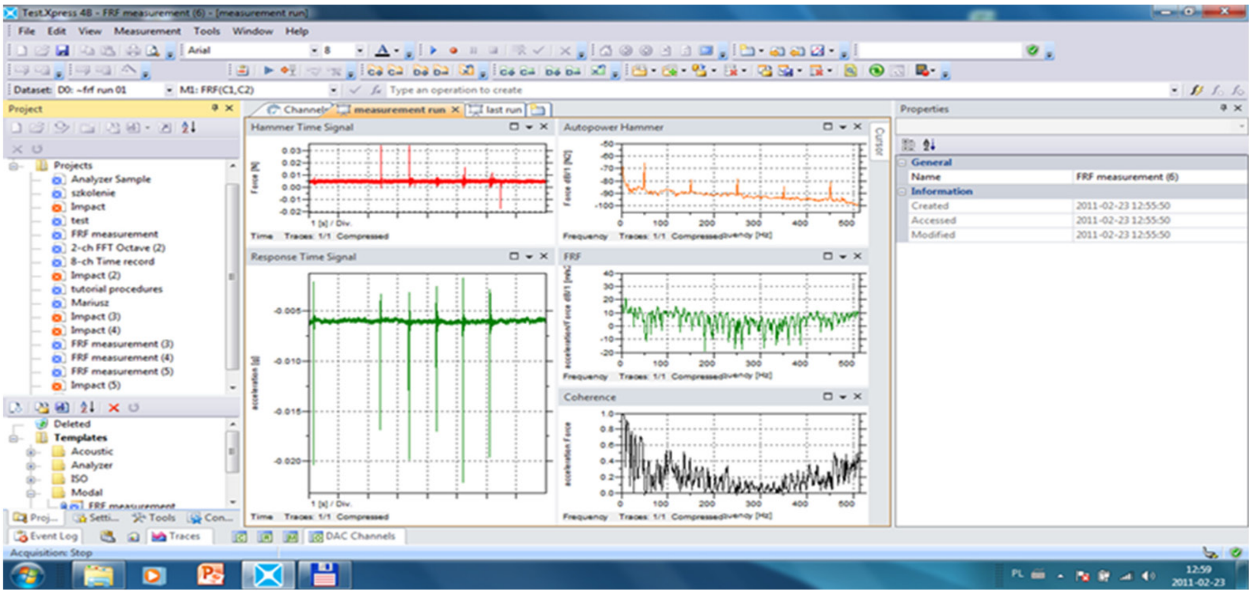

Fig. 2. Software front panel

Source: ©Siemens Simcenter Testlab software.

– five times is shown the FRF for good, and five times for destroyed brick element. In Figure 4, the extortion and the answer of signal in time domain that allows gaining FRF is shown (once).

Graphic results, which show FRF of good and destroyed bricks measured in axis Y, are shown in Figure 5 – five measurements for each material sample.

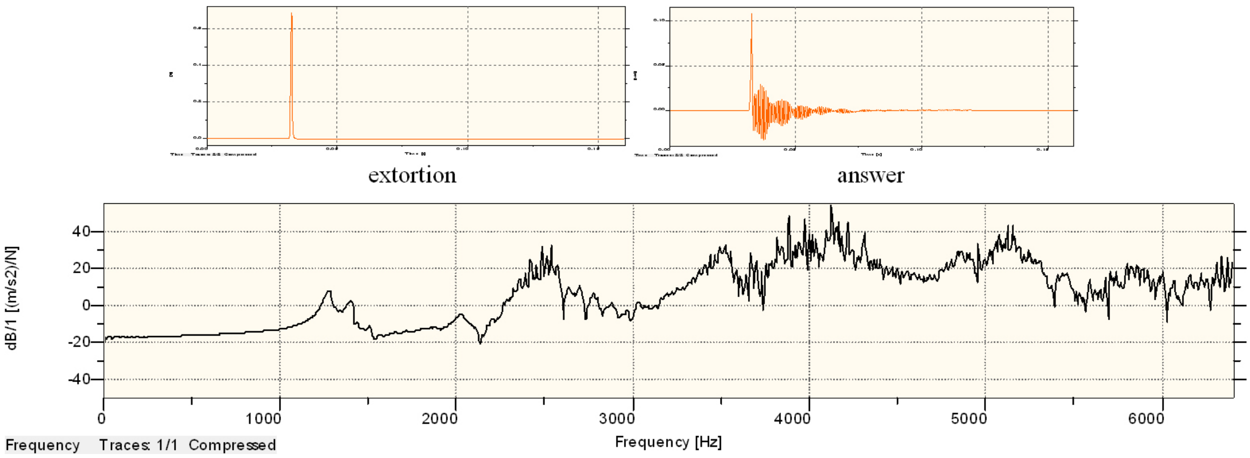

Fig. 3. Example exposition of results of measurement – own study

Source: own tests performed with the Simcenter Testlab software.

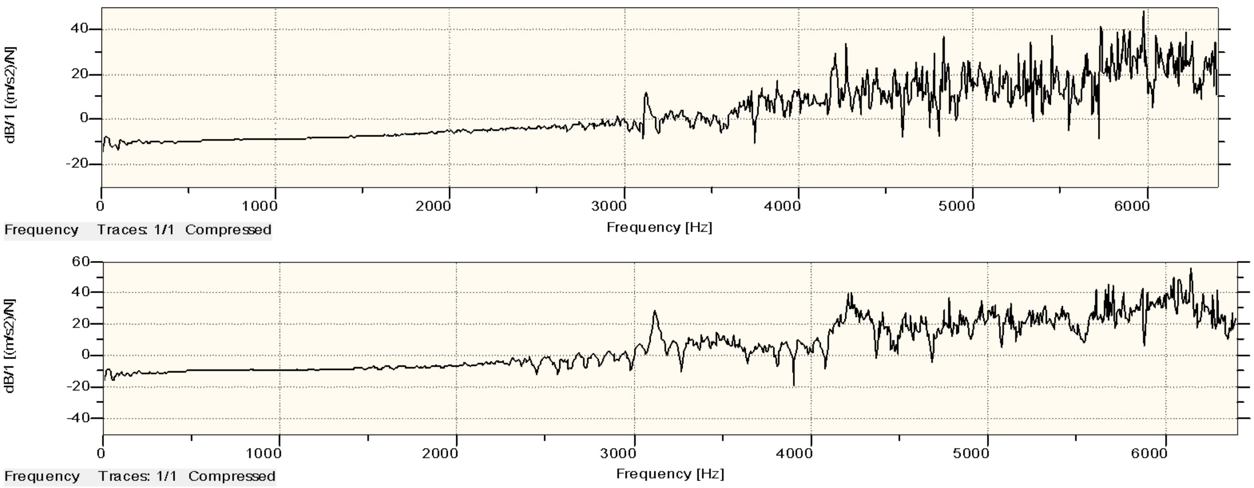

Fig. 4. Composition of results of measurements (the temporary course of extortion, temporary course of answer, the FRF) the full brick in axis Y

Source: own tests performed with the Simcenter Testlab software.

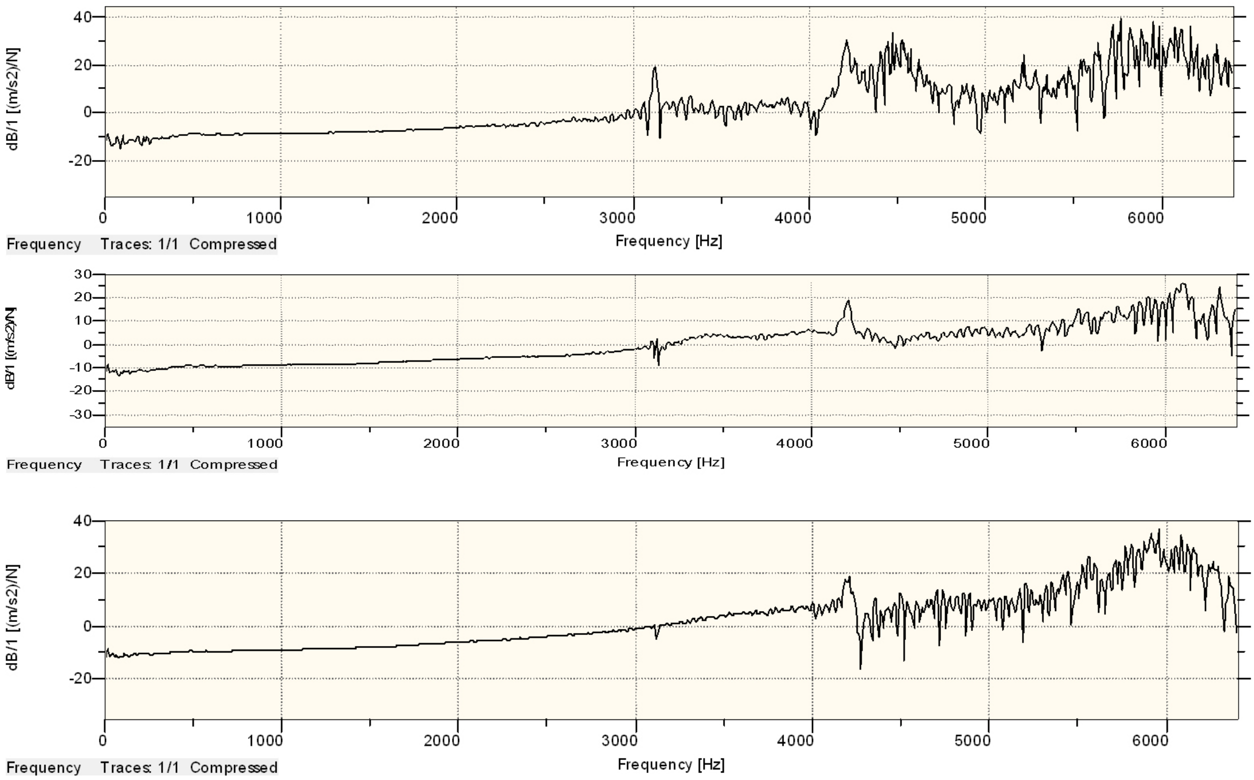

Fig. 4. (cont.)

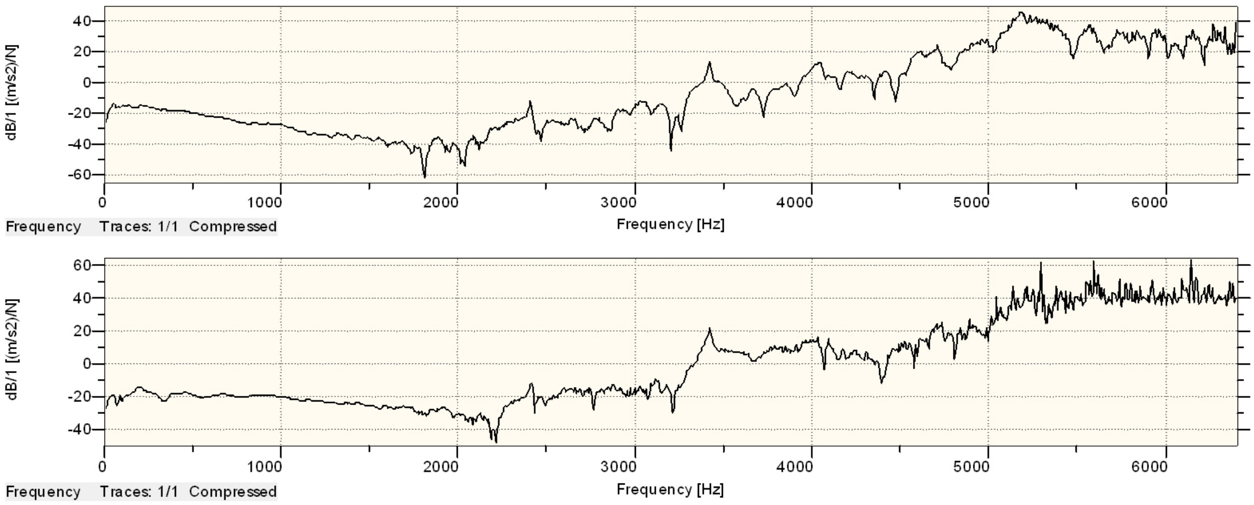

Fig. 5. Composition of FRF of destroyed full brick in axis Y

Source: own tests performed with the Simcenter Testlab software.

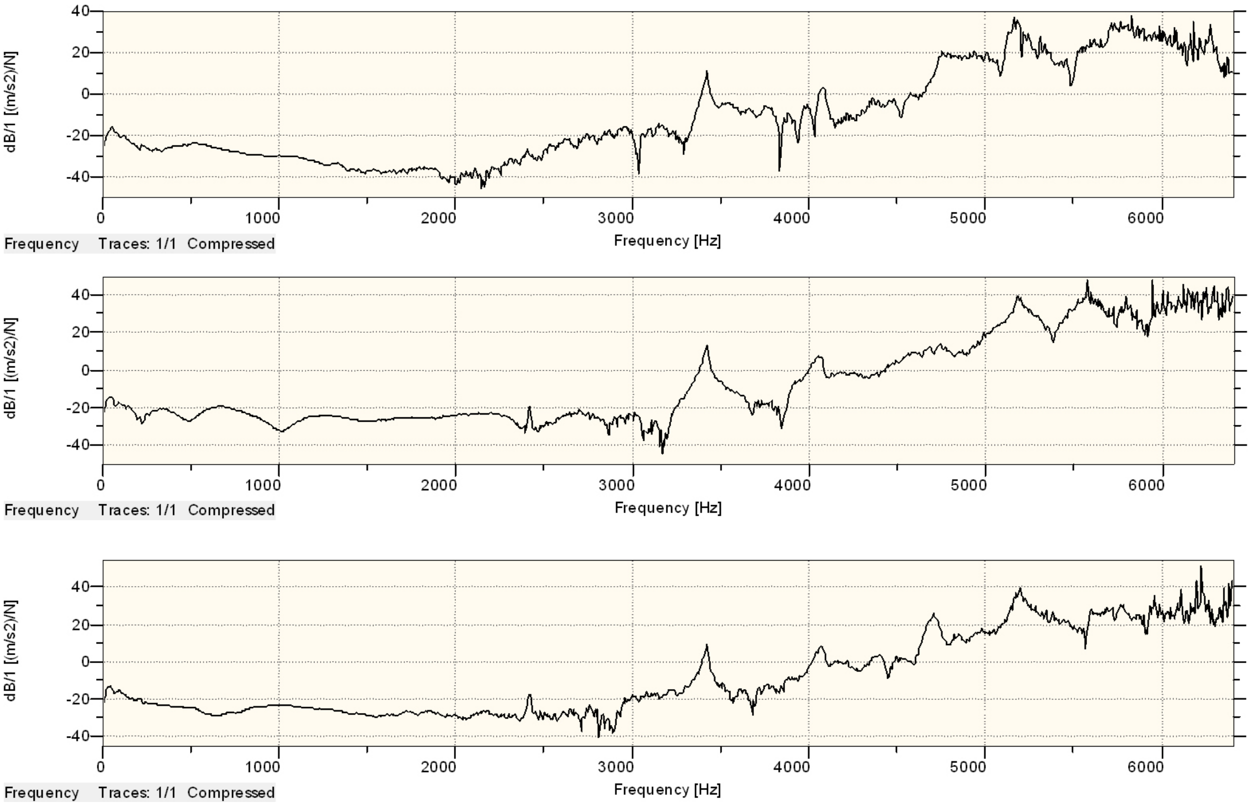

Fig. 5. (cont.)

CONCLUSIONS

The results point to the fact that it is possible to distinguish between material properties, which impacts the ability to distinguish between their mechanical properties. The study also confirmed the usefulness of the LMS test apparatus using operational modal analysis performed on the actual building construction.

By obtaining graphical charts of FRF, and later their comparison, it is possible to observe their diversity. These charts are different for materials that are in good and damaged condition, which demonstrates the ability to assess the destruction of a brick element.

The graphical course of the FRF for damaged elements has a significantly different course than the graphical presentation of the FRF for remote elements, which allows clearly determining whether the tested element is damaged or not. The damage is clearly manifested by the undulation of the function arising at the level of 2,000 Hz, while the serviceable elements show the undulation at the level between 3,000–4,000 Hz.

It practically verified the sensitivity of the assessment of modal analysis to the degree of brick structure degradation. It becomes possible to determine hazards to a building structure based on examining values of frequencies.

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POMIAR DRGAŃ W BADANIU DEGRADACJI MATERIAŁÓW BUDOWLANYCH

STRESZCZENIE

Obiekty ceglane podlegają dużym obciążeniom dynamicznym, czego rezultatem są procesy wibracyjne. Drgania mogą wpływać na stan zdatności użytkowej obiektów poprzez zmniejszenie komfortu pracy użytkowników, a także możliwe osiągnięcie poziomu zagrażającego bezpieczeństwu obiektów. Oddziaływanie drgań na konstrukcję objawia się głównie dodatkowymi naprężeniami w danym przekroju poprzecznym, które sumują się z wynikającymi z obciążeń statycznych. Obciążenia dynamiczne mogą powodować niszczące skutki w budynkach o różnych typach konstrukcyjnych, a nawet prowadzić do ich zniszczenia. W artykule opisano serię autorskich analiz procesu niszczenia wybranych obiektów murowanych metodą eksperymentalnej analizy modalnej. Badania przeprowadzono w celu udoskonalenia oceny jakości konstrukcji budowlanych pod kątem stanu technicznego konstrukcji murowanych oraz spełnienia parametrów bezpieczeństwa.

Słowa kluczowe: analiza modalna, częstotliwość drgań własnych, wykres stabilizacji, drgania konstrukcji