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Use and potential of the digital twin of Structural Health Monitoring and Non-Destructive Testing for improving durability and preventing failures of existing structures

Wykorzystanie i potencjał cyfrowego bliźniaka do monitorowania stanu konstrukcji i badań nieniszczących w celu poprawy trwałości i zapobiegania awariom istniejących konstrukcji

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Abstract. In this article, we consider the application of Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT) in existing facilities. Based on the literature and our own experience, the issue of structural monitoring is discussed with regard to the direction of this application in the context of further implementing digital twins in the future. The general algorithm and procedures in such a process and considers the impact of continuous monitoring on durability of the object. Building information modelling, structural health monitoring (SHM), 'Non-Destructive Testing' (NDT) are discussed. The whole is based on structures that are extremely important to the industry, such as industrial chimneys. In this article, we discuss an approach to automating the condition inspection process of existing facilities in the context of information management and the use of this information. Reference was made to examples of condition analyses of two steel chimney structures.
Keywords: Non-Destructive Testing (NDT); chimneys; digital twin; existing structures; Structural Health Monitoring (SHM).

Streszczenie. W artykule rozważane jest zastosowanie Structural Health Monitoring (SHM) oraz Non-Destructive Testing (NDT) w istniejących obiektach. Na podstawie literatury i własnego doświadczenia, zagadnienie monitorowania konstrukcji- zostało omówione w odniesieniu do kierunku tego zastosowania w kontekście dalszego wdrażania cyfrowych bliźniaków w przyszłości. Przedstawiono ogólny algorytm i procedury w takim procesie oraz rozważono wpływ ciągłego monitoringu obiektu na jego trwałość. Omówiono modelowanie informacji o budynku, monitorowanie stanu konstrukcji (SHM), badania nieniszczące (NDT). Całość bazuje na konstrukcjach niezwykle ważnych dla przemysłu, takich jak kominy przemysłowe. W artykule omawiamy podejście do automatyzacji kontroli stanu technicznego istniejących obiektów w kontekście zarządzania informacją i wykorzystania tej informacji. Odniesiono się do przykładów analiz konstrukcji dwóch stalowych kominów.
Słowa kluczowe: badania nieniszczące (NDT); kominy; cyfrowy bliźniak; istniejące konstrukcje; monitorowanie stanu konstrukcji (SHM).

Industrial chimneys play a vital role in various industries, and their structural durability is crucial for a country's development. Surprisingly, they are often overlooked in discussions regarding the application of SHM or digital twin compared to residential construction [1 – 8]. However, their durability is essential for advancing technologies and industry growth. This article focuses on the use of digital twin of Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT) in existing structures in the context monitoring and supporting ongoing renovations. This approach extends the structure's lifespan, prevents failures, and ensures safe decommissioning. While the collection of object information and its implementation in modelling currently more geared towards new projects, its application in existing buildings during their lifecycle or renovations is becoming essential. The article explores condition monitoring in industrial structures, particularly steel chimneys, and discusses topics like Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT). SHM uses sensors to predict or detect defects, while NDT characterizes structural integrity without causing degradation.

Considering facility management and technical maintenance, continuous structural monitoring is crucial. We will look at the importance of Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT) for the durability and reliability of these structures such as industrial chimneys, using a selected example of measurements.

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Characteristics of chimneys

Chimneys in industrial plants are commonly used for the disposal of steam and chemical vapors, depending on the industry. These chimneys require maintenance to ensure industrial safety and reduce the risk of accidents. To renew and maintain existing installations, the use of monitoring tools that are enhanced with data management functions can be innovative in this sector. Ultimately, modelling that allows the introduction of continuous condition monitoring of specific elements or zones can bring significant benefits to the sector.

There are two commonly used types of chimneys: self-supporting chimneys (Photo 1) and steel chimneys with guy wires [9], which serve to provide stability to the main structure by transferring wind and seismic forces. The first set of collars is attached at one-third or one-fourth of the height from the top. Subsequent sets (if there is more than one) are then located at different heights.

Photo 1. Self-supporting steel chimney with a height of 80 m [1]
Fot. 1. Wolnostojący komin stalowy o wysokości 80 m [1]

Considering remote monitoring of structures, we must be aware of the main causes of their damages. In the case of the mentioned chimneys, the factors determining degradation are wind actions influencing the deformation and displacements of the object and corrosion, which causes changes on the surface of the chimney's shell and its material structure. According to EN 1993-3-2, a distinction is made between external and internal corrosion, resulting from external environmental impacts and the effects of gases inside the chimney, respectively. Due to the cylindrical structure and height of the chimney, the significance of crosswind is also considered as longitudinal wind with the same characteristics, as shown in Figure 1. It can cause structural deflection, which is limited by EN 1993-3.2. If the chimney is immersed in a flow, forces induced by vortex shedding will cause cylinder oscillation. This movement leads to vibrations triggered by vortices [10]. Depending on boundary conditions, wind velocities, and the natural frequency of the structure, the chimney may vibrate only in the longitudinal direction, only in the transverse direction, or oscillate in both directions. This can result in vibration amplitudes of the structure, which are also limited by Eurocode – Annex E-EN 1991.1.4 paragraph 1.5.3. An example of the authors' research on pressure and velocity distributions for the cylinder with Re = 10000 is presented in Photo 2.

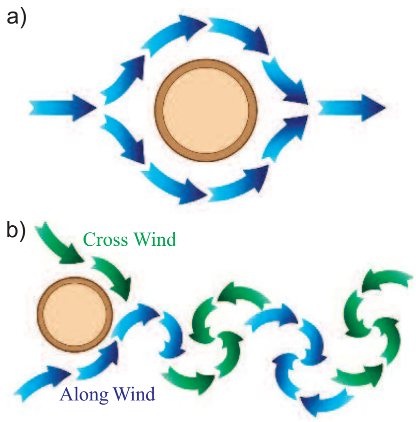

Fig. 1. Graph of the force acting on the chimney cross-section: a) along the wind, b) vortex shedding *[Fig. own work]*
Rys. 1. Wykres siły działającej na przekrój komina: a) strumień wzdłużny wiatru; b) strumień wirowy [Rys. opracowanie własne]

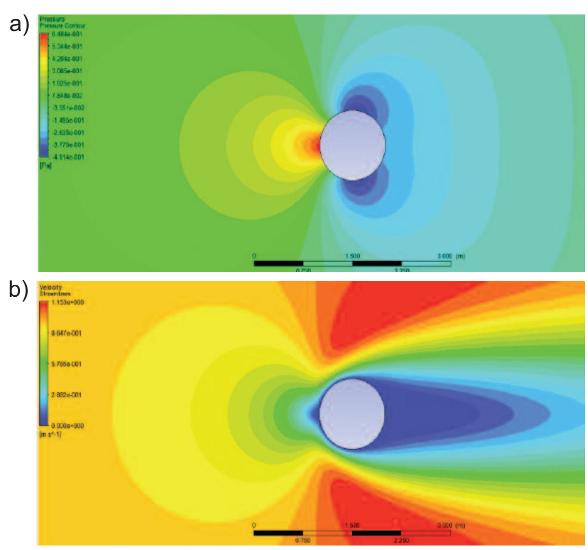

Photo 2. Pressure contours (a), velocity contours (b) for the cylinder, at Re = 10000 *[Photo: authors]*
Fot. 2. Kontury ciśnienia (a); kontury prędkości (b) dla cylindra, przy Re = 10000 [Fot.:autorzy]

Monitoring

Therefore, by understanding the main causes of damages, we can seek ways to control and reduce them. Structural Health Monitoring (SHM) is the process of monitoring the structural integrity by placing sensors to predict or detect the appearance of defects. It is based on Non-Destructive Testing (NDT) technologies to diagnose the technical state of the structure. SHM enables predicting structural degradation to avoid accidents. These sensors are connected to signal processing systems and result analysis to facilitate maintenance and optimize the integrity and lifespan of products [12]. SHM is, therefore, part of both cost-saving and precautionary strategies for industries and institutions. It also serves as a tool for forecasting structural changes and estimating its service life.

Examining the technical condition of structures usually occurs when dealing with a faulty structure and aiming for a thorough design of repair or reinforcement. Monitoring characteristic parameters of aging or damages is typically carried out within „targeted inspections". Monitoring requires a more detailed analysis of the structure and a thorough examination of anomalies found during monitoring activities (including recent detailed inspections). The first step is to conduct a preliminary visual diagnosis and evaluate possible or even probable causes of occurring irregularities. This allows us to select the appropriate diagnostic methodology and measurement techniques to be applied. Often, the combination of NDT techniques (usually qualitative) and quantitative techniques **applied to samples proves to be the most beneficial**. Non-Destructive Testing is a set of methods that enable characterizing the integrity of structures or materials without damaging them, using sensors.

The challenge for SHM is to make structures smarter by diagnosing their health and evolution beyond simple measurements. By incorporating algorithms or software, we can provide a qualitative or quantitative understanding of the structural condition [13]. Although BIM has wide applications in the construction industry and there are numerous digital twins of various types of objects, our literature review indicated that this issues has not been widely used in the construction of steel chimneys [14 – 20]. Thoughtful and appropriate implementation of digital twincan make the data collected in SHM also useful at the operational stage for facility managers and understandable for practitioners not directly involved in condition surveys.

Tools for monitoring

Measuring equipment (sensors) should be installed after inventory to determine the current condition and establish threshold values for parameters. Calibration is essential for accurate real-time control. Individual calibration for each structure is necessary due to varying locations and geometries. An experienced civil engineer should conduct calibration and analyses according to standards. This tool enhances analytical capabilities, enabling timely responses to changing parameters, extending the structure's lifespan through proper maintenance.

Tilting and deflection allow for checking long-term stability by measuring displacements at several precise points. Structural fatigue is analyzed to avoid component cracks after a certain number of cycles or damages in specific areas. Specific to the material, steel is examined for corrosion and expandability to verify its internal strength. Finally, as part of a broader structural assessment, water or gas leaks are checked to prevent structural or physical damages. The values obtained through monitoring tools are compared with the structural limit values determined according to standards.

SHM can be conducted using dynamic structural analysis with the utilization of an accelerometer system (Photo 3b). Photo 3a depicts the analyzer system with the results of chimney vibration analysis. The measurements made in situ can allow for comparison of chimney parameters to the results achieved in the design phase.

a)

b)

Photo 3. Structural dynamical system (a) analyzer; (b) accelerometer *[Photo: authors]*
Fot. 3. System dynamiki konstrukcji (a) analizator; (b) akcelerometr
[Fot.: autorzy]

Method of monitoring

SHM is a multidisciplinary approach that integrates all methods, techniques, technologies, and disciplines aimed at assessing the integrity, technical condition, and maintenance of structures over time to detect and predict their failures, thus extending their lifespan. Complete monitoring of structures involves three key steps:

■ initial inventory;
■ continuous monitoring of the evolution of the construction's condition;
■ conclusion regarding remedial measures.

This methodology serve several purposes, such as:

● understanding the static and dynamic behavior of the structure;
● locating and identifying individual areas of concern;
● defining the original structural signature of the structure;
● determining the optimal sensor locations.

After processing through highly accurate algorithms and expert analysis, this data is used to assess the technical condition of the structure and set related alarm thresholds, which can be directly used by all stakeholders (managers, service providers, engineering firms). Utilizing this dynamic data allows for interpreting the real behavior of the structure and monitoring its evolution in real-time, enabling the early detection of anomalies not visible to the naked eye.

Algorithm

As an example, let's present a general algorithm for calculations that an application can perform based on the parameters received from sensors:

■ general inventory of the structure (determining the actual condition and limit values);
■ installation of sensors;
■ calibration of the computational/analytical scheme in the measurement-supporting application;
■ reading measurements from the sensors;
■ analysis within the application using selected software;
■ final information on the measurement value and its comparison to the limit values.

Throughout the entire process, human involvement is essential at the beginning and the end. In the initial phase, a civil engineer is necessary to conduct the preliminary inventory, install the sensors, and calibrate the application. In the final phase, the engineer should analyze the information obtained from the application and make the ultimate decision regarding the structural condition and further operation. In the case of an unsatisfactory condition, recommendations for reinforcement, repairs, or maintenance should be provided. After the first completed process in this manner, it should loop back to the stage of sensor measurements and create a continuous cycle of guiding the objects.

Real parameters such as wall thickness allow determining the actual condition of the object. This stage serves as a good starting point for the proposed method of structural monitoring. Conducting a detailed analysis will help establish computational algorithms and threshold values necessary for calibrating the application. The wall thickness in the analised segment is derived from measurements, in this case, obtained during the inventory, which enables the creation of an analytical model of the object. This way, we replicate the actual condition of the object, allowing us to create a model and gather all the loads acting on it. This not only facilitates the assessment of the current condition but also enables the prediction of its future durability. For instance, with such a model, one can determine if a certain wall thickness fails to meet strength requirements. Considering the three values: **the measured thickness**, **the minimum thickness** according to EN 1993, and **the thickness at which loss of load-bearing capacity occurs**, it is possible to establish a comparative range for each subsequent measurement. In the same way, we can determine the maximum force the object can withstand, maximum deflection, etc., and these values can serve as references in subsequent operations.

The first example is a steel chimney with lashings with a total height of 45.00 m. On the basis of data obtained from an expert opinion to assess the technical condition of the object and to evaluate its continued trouble-free operation, the structure of the object was analysed. This information allowed the facility to be modelled in Robot Structural

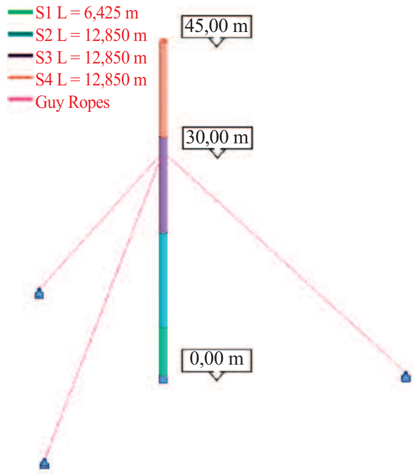

Fig. 2. Image of the steel chimney model

[Fig.: authors]

Rys. 2. Model komina stalowego

[Rys.: autorzy]

Analysis Professional, the model of which is shown in Figure 2. Lashings in the form of three Ø25 mm steel cables were fixed at a height of 30.00 m and to the foundation blocks, which was modelled as a restraint. The chimney shaft with a fixed diameter of 1120 mm consisted of 4 segments, which is also shown in Figure 2. The model thus created was used to apply the analytically determined load most determinant in such structures, which is the wind load. Such analyses made it possible to determine the theoretical maximum forces occurring in the chimney structure as a result of the basic wind and self-weight loads, as shown in Figure 3.

Based on the expert opinion, a deflection of 56 mm was measured. Compared to the result obtained by numerical simulation, which was 58.4 mm, it can be concluded that the permissible value was not exceeded. Nevertheless, it is advisable to analyse the situation more closely to ensure that the calculated safety margin of 2 – 3 mm is not breached, allowing the structure to function in the long term without failure. The example presented highlights the importance of comparing measured and calculated values to prevent failures. One proposed solution in such a case is to install continuous monitoring sensors that are linked to a real-time information transfer system, as discussed in previous sections of the article.

Another example concerns a steel chimney 80 m high, which was subjected to vibration testing [10]. Accelerometric sensors with a range of 0 to 1,000 Hz and a sensitivity of +/- 10g were used for the measurements, and the analyses were carried out. Accelerometric sensors are accelerometric devices that can detect and measure changes in the velocity of objects on which they are mounted. The sensors were installed at three levels: 1 , 5 and 10 m below the top of the chimney. The vibrations of the chimney were mechanically induced, followed by a series of test and calibration measurements. The fundamental resonant frequencies at the test points were f = 0.32 [Hz]. The frequencies were measured to an accuracy of 0.02%.The basic resonant frequency of 0.32 Hz , the reading for a sensor at 1 m from the top of the chimney is shown in Figure 4 [20-22].

Design calculations show that the fundamental natural frequency is 0.31 Hz [10]. Comparison of the calculated value with the measured value provides information on the technical condition of the structure and gives an idea of the accuracy of these calculations and measurements. The measured value is close to the calculated value at the

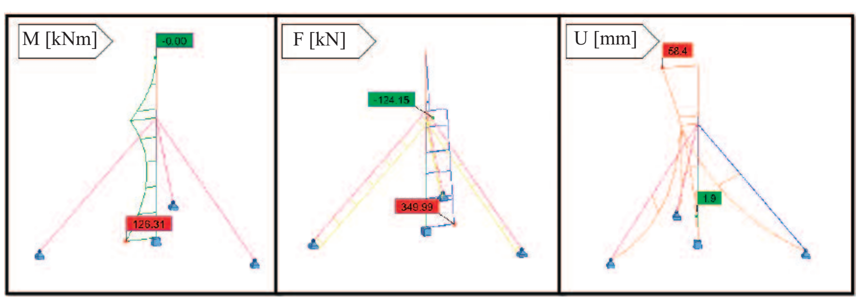

Fig. 3. Graphes of force in chimney

[Fig: own work based on picture from Robot Structural Analysis]

Rys. 3. Wykresy sił w kominie

[Rys.: opracowanie własne na podstawie rysunku z Robot Structural Analysis]

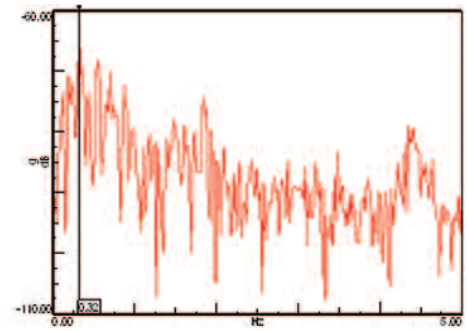

Fig. 4. The basic resonant frequency of 0.32 Hz, the reading for a sensor at 1 m from the top of the chimney [21 – 22]

Rys. 4. Podstawowa częstotliwość drgań rezonansowych 0,32 Hz, odczyt dla czujnika znajdującego się w odległości 1 m od szczytu komina [21 – 22]

design stage. The information gathered in this way confirms the algorithm discussed in the above section and emphasises the importance of checking the technical condition of the structure at the use stage with reference to the design condition.

Conclusions

The innovative approach to the management of infrastructure and structures is based on the application of automation to the control and monitoring processes, resulting in significant long-term cost savings, a significant increase in safety levels and an extension of the life of the facilities. The implementation of systems for the continuous monitoring of structures enables the early identification of potential anomalies and failures, which allows a rapid response and the implementation of necessary corrective or reinforcing actions, significantly contributing to extending the life of these facilities. Automating processes such as periodic maintenance not only increases the accuracy and efficiency of structural health monitoring, but also minimises the risk of human error often associated with traditional assessment methods. Technologies such as Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT) play a key role in the prevention of damage and failure, which not only enables rapid repair and preventive action, but also enhances occupant safety and environmental protection. In addition, the systematic collection of data on changes in key structural parameters allows more accurate prediction of their behaviour, which is invaluable for the purposes of optimising engineering designs. As a result, engineers and designers can use the information gained to create more sustainable and safer structures, while promoting sustainable construction practices. Continuous observation and monitoring of building structures not only extends their life cycle, but also supports the idea of sustainability by encouraging existing structures to remain in good working order for as long as possible. Such a strategy contributes not only to the conservation of natural resources, but also to reducing the need to exploit new sites, which is crucial in the context of the planet's limited resources and growing environmental awareness.

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