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A Structural Health Monitoring System Based on an Analysis of Changes in the Static, Dynamic and Magnetic Properties of the Structure

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Abstract

The complexity and diversity of civil engineering structures imposes requirements on the diagnostic system, which are difficult to satisfy. In this paper the concept of a distributed diagnostic system capable of monitoring the technical state of critical elements of large infrastructure objects such as steel trusses, supermarket buildings, exposition halls, bridges etc. is discussed. The main difference compared to the structure and rules of a classical diagnostic system is the introduction and use of the mathematical model and the physical test objectives in the entire diagnostic process. The model is based on the analysis of the behaviour of a technical object and the physical phenomena associated with it. The current results show that taking into account necessary knowledge, it becomes possible to recognise the qualitative and quantitative changes in the signals generated by the object that are linked to the degradation processes.

Keywords: diagnostic systems, magnetic methods, construction monitoring, civil engineering, structural health monitoring.

1 Introduction

Structure health monitoring (SHM) of civil engineering structures is an important issue due to a rapid development of the modern building techniques with constant tendency to increase their dimensions and surface loading of the constructions. The designers are pushed to lower the construction costs while simultaneously increasing the variety of used architectonic concepts. Additionally the growing number of buildings, structures, and bridges are reaching or have exceeded their expected life cycle. These all circumstances leads to the possibility of catastrophic accidents with casualties and death of people and indicate the necessity to elaborate the new methods of monitoring the technical state of such objects.

In the last years several SHM systems were installed on the large scale civil engineering structures. Depending on their goal they could be roughly divided into two kinds: systems focused on monitoring aged structures that are exceeded their expected life cycle and systems installed on brand new constructions. First group is usually focused on monitoring structure failures like cracks emerging in the construction. Two examples of such systems are systems implemented on the Götaälv Bridge in Sweden and on the Brooklyn Bridge in New York. Götaälv Bridge is a steel girder bridge with concrete bridge deck built in 1939. The steel girders of the bridge suffer from fatigue, also some cracking have taken place in the construction. The monitoring system installed on the bridge is therefore focused on strain temperature and crack measurements. It measures strain profiles along the whole length of the bridge and detects cracks that are wider than 0.5 mm [1]. Brooklyn Bridge, built in 1883, was constructed over a series of increasingly taller and longer brick masonry vaults that are suffering from longitudinal crown cracks covering the entire lengths of them. Implemented system monitors key structural parameters such as crack opening displacements, wall rotations, floor movements, structural vibrations and temperature fluctuations [2]. Both systems are using fibre optics Bragg sensors for measurements of displacement, cracks and temperature.

Systems installed on the newly built structures are usually monitoring stress and vibrations in the construction and are focused on global health assessment of the structure. Adopted diagnostic methods are usually based on the calculation of the dynamic properties of the structure such as natural frequencies, damping ratios and mode shapes [3–7]. These systems are frequently installed in the regions with harsh atmospheric conditions or in seismic active areas. An example of such system is the Rion-Antirion Bridge monitoring system [8], the bridge built in the extremely seismic area of the Corinth Strait in Greece. Its monitoring system is focused on measuring the behaviour of the bridge during normal operation, strong winds existence, and earthquakes. It consists of a network of National Instruments PXI/SCXI real time controllers equipped with different kind of sensors:

- 3D accelerometers on the deck, pylons, stay cables, and on the ground for wind and seismic tremors measurements,
- strain gages and load cells on the stay cables,
- displacement and temperature sensors on the expansion joints to measure the thermal expansion of the deck,
- LVDT sensors on the stay cables to measure movement,
- load cells on the restrainers for recalibration in the event of an earthquake
- the weather stations measuring wind intensity, direction, air temperature, and humidity [8].

The China Donghai Bridge, one of the world's longest bridges with a length of 32.5 km, is equipped with a system performing continuous structural health integrity monitoring. It analysis the response of the construction to environmental factors in an environment prone to typhoons, earthquakes, and corrosive saltwater[9]. It is built around 14 PXI controllers synchronized with GPS satellites[10]. In this system data analysis is performed online with offline support. Online analysis consist of real time calculating resonance frequencies as accelerometer data is collected. For this purpose recursive Stochastic Subspace Identification [5,11,12] algorithm is used. Resonance frequencies of the bridge are then constantly monitored for any changes that could be linked to the faults of the structure. Diagnostic process is supported by offline operational modal analysis with use of collected data to reflect the dynamic properties of the bridge (resonance frequencies, damping ratios, and mode shapes).

Similar diagnostic systems were installed on 2008 Summer Olympic venues in Beijing including both the Beijing National Stadium and the Beijing National Aquatics Center, the 104-story World Trade Center in Shanghai, the 66-story Park Hyatt Hotel complex in Beijing, the 240 m concrete arch dam in Ertan and the 8266 m cable-stayed bridge in Shantou [13]. As these structures were built in the seismic active areas their diagnostic systems were focused on structural health characteristics, including stability, reliability, and liveability. They were built around National Instruments cRIO controllers as a high number channel systems capable of simultaneously acquire signals from 36 to 64 acceleration channels. GPS receivers ensure ±10 µs interchassis synchronization between controllers.

In structural health monitoring of civil engineering structures various methods of technical state assessment could be used. Usually they are based on the comparative tensometric (strain gauges and/or FBG optic fibres) and dynamic (acceleration signal) measurements. All these measurement methods are focused on stress assessment in critical fragments of the structure that are vital for its stability and durability. Evolution of defects in the construction additionally causes measurable changes in its dynamic properties along with evolution of stress distribution in critical construction joints.

The diagnostic system presented in this paper presents an original concept of a comprehensive diagnostic approach that could increase the reliability of diagnosis of early stages of construction defects. The main difference compared to the structure and rules of a classical diagnostic system is the introduction and use in the diagnostic process of the mathematical model and the physical test object. The model is based on the analysis of a technical object behaviour and the physical phenomena associated with it. The current results shows that taking into account necessary knowledge, it becomes possible to recognize the qualitative and quantitative changes in the signals generated by the object that are connected to the degradation processes.

2 Structure of the SHM distributed diagnostic system

Most of diagnostic systems mentioned above were constructed as a distributed systems. Such systems are widely used in machine diagnostic for monitoring condition of critical machines e.g. power units, fans, etc. allowing on-line monitoring and performing exploitation decisions according to the current state of the monitored objects [14]. The main advantage of this approach is the possibility of monitoring the technical state of many machines distributed on a large area from one place thus limiting costs and manpower. Especially it affects cases when there are long distances between machines and a diagnostic technician. This concept was adopted to the monitoring of civil engineering constructions that are typically spreaded over large area (Fig. 1). The reason for using this layout is the usual dispersion of the measuring points in the diagnosed construction imposing excessive length of sensor cables. Maximal length of electric sensor cables is usually limited to about 100m (ICP/IEPE accelerometers, strain gauges etc.). Comparing this limit to the dimensions of typical civil engineering structures it is clearly impossible to implement the data acquisition (DAQ) system with a star topology, i.e. a single DAQ device with many sensors. Instead DAQ system should be divided into parts covering selected fragments of the structure. An exception to this is usage of fibre Bragg grating (FBG) sensors for temperature, crack and strain measurements [1]. As they are using single mode fibre optics their length is practically unlimited comparing to the size of typical objects.

A distributed diagnostic system consists of several programmable units monitoring construction elements or machines. These units are built on the microprocessor controllers basis equipped with signal conditioning circuits. Signal conditioning should be chosen according to the used signal sensors measuring values linked to the objects technical state. Depending on the diagnostic algorithms implemented in the system these units could be simple DAQ devices registering and transmitting acquired sensor values over the network (eq. wireless DAQ devices), data preprocessing units compressing information (e.g. calculating spectra) or units performing diagnostic tasks on the elements of the structure. Detailed structure of the system depends on the tasks performed by the controllers. If data synchronization is required proper care should be taken to implement shared clock and common data triggering. This could be accomplished either by distributing clock signal over the network or using GPS PPS (Pulse per Second) synchronizing signal [10].

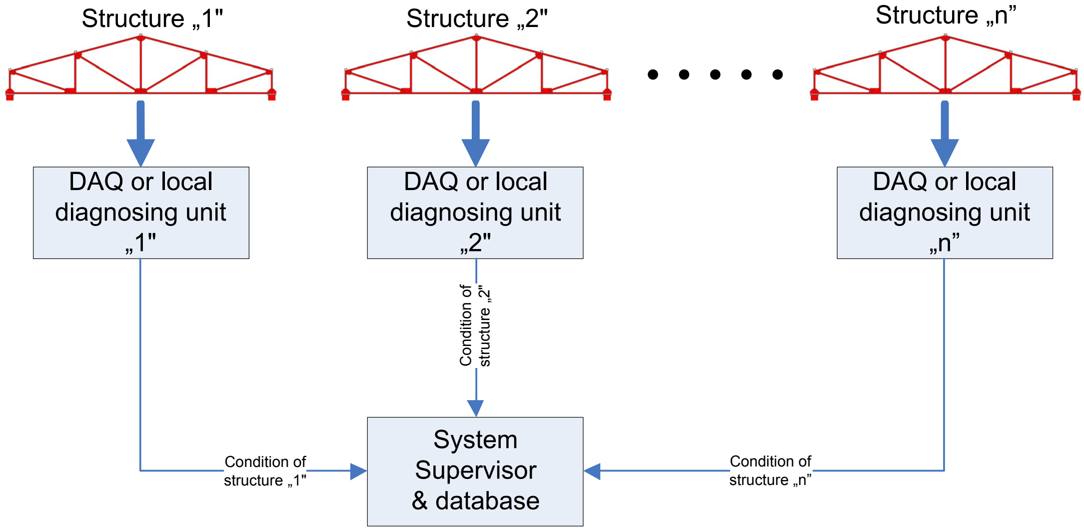


Figure 1: Schematic layout of the distributed diagnostic system [15].

Local diagnostic units usually have the capability of communicating with each other and the environment using TCP/IP network. Through the network the diagnostic units are informing users and the managing unit about the current technical state or load of the structures and the exploitation decisions they actually made. TCP/IP network additionally allows authorized persons, e.g. external experts, to access the system from its outside. Using TCP/IP network is also relatively easy to implement the automatic messaging modules (e-mail, SMS, etc.) informing authorized personnel about the current problems with the monitored objects. Network could be also used for communication with external database storing processed measurement results and information about current technical state of the structure and its current load. Such solution helps relieve the controller from the necessity of handling the local database and allow limiting hardware requirements.

All the controllers are connected to a system supervising unit, main processing unit usually with the database server, performing final diagnostic decisions and storing information about the changes of technical state of the construction. This server is accessible to the technical staff taking care of the diagnosed infrastructure objects and being able to undertake proper exploitation decisions. An advantage of this approach is that the local diagnosing systems, as of Fig. 1, could easily be expanded into bigger e-monitoring network.

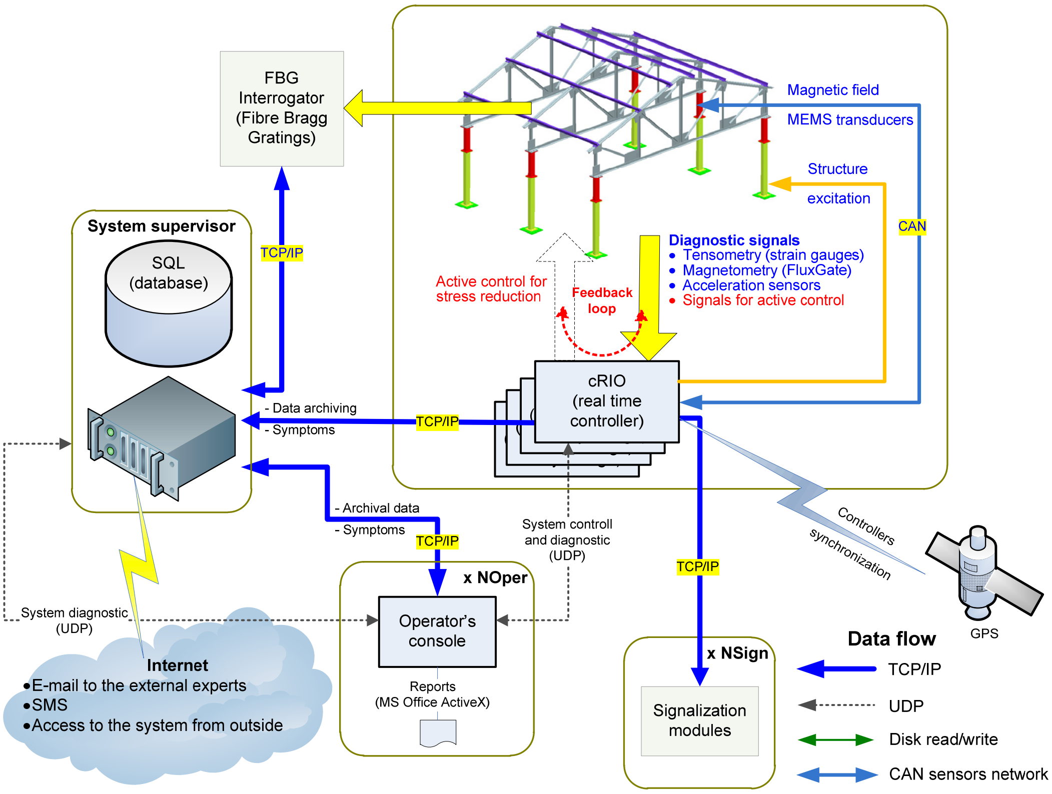


Figure 2: Layout of the SHM system

2.1 Layout of the developed system

Diagnostic system proposed in this paper is designed according to the schema presented on Fig. 1. It is built in a form of a network of autonomous National Instruments cRIO real time controllers equipped with data acquisition modules. Controllers are acquiring data with programmed intervals from strain gauges, acceleration sensors and Applied Physics Systems APS-536 FluxGate magnetic field transducers applied to the girders of the construction (Fig. 2). Additionally each controller acquires data transmitted through the local CAN network from specially built low cost MEMS magnetic sensors applied to the joints of the construction (Fig. 3). Relying on the acquired data, controllers are evaluating stress in the selected construction points, overall loading, and current state of the construction. Post processed data are then transmitted through TCP//IP network to the supervising server with SQL database. Remote steering of the controllers and system diagnostic is performed through commands and information transmitted as UDP packets.

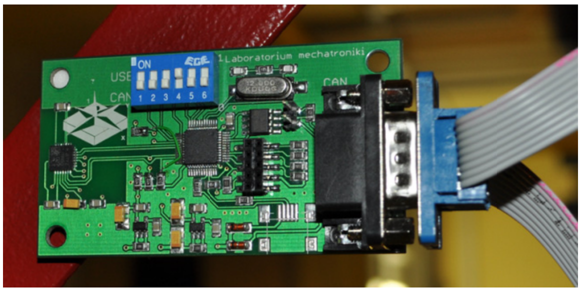


Figure 3: Magnetic sensor with MEMS technology (ARM processor, measuring range 8 Gauss, max. frequency 75Hz, CAN interface)

Optionally controllers have the possibility to excite the construction for the purpose of modal analysis. This could be done automatically with predefined intervals or manually on the request from the supervising unit. In this case data acquisition process on the controller is synchronized with the impulse timing.

If needed, data synchronization between controllers could be obtained through the use of GPS receivers [10].

Stress in the construction could additionally be measured using fibre optics FBG sensors with temperature compensation. The FBG interrogator is connected to the system supervisor unit using TCP/IP network.

2.2 Methods of stress assessment in ferromagnetic construction

Ferromagnetic materials that have risk of damage due to material fatigue, exceeding maximum stress or plastic deformations have magnetic properties, which could be used for construction diagnostics - mainly for stress assessment. Depending on the source of the magnetic field these methods could be divided into active and passive methods. Active methods requires application of artificial source of magnetic field, rather sophisticated and expensive equipment used mainly in offline testing procedures [16]. Passive methods has all the advantages of active diagnostic methods and additionally they does not require the application of artificial source of magnetic field. Passive magnetic methods work primarily on the basis of interaction with the Earth’s magnetic field. Despite of the low signal values, when the stress factor in the ferromagnetic material has been changed the changes of its magnetic state may also be analyzed from a distance. This leads to the conclusion that the characteristic properties of passive diagnostic methods described above may be used for online monitoring of large construction structures.

The relation between stress and the degree of magnetization is highly complex. It depends also on the type of material and its temperature. Every physical object within the magnetosphere interacts with Earth's magnetic field and is subjected to special laws of physics [17]. Such objects can attract or deflect magnetic field lines around them. Own magnetic field (1) of an object is

$$\mathrm{H} = -\mathrm{grad}(\mathrm{w}) \tag{1}$$

where, w is the magnetic potential (2), a function of the gradient of magnetization

$$\mathrm{w} = \mathrm{div}\,\mathrm{M} \tag{2}$$

Hence, object's own magnetic field H measured by a magnetometer depends on the object's magnetization and its distribution in the space. Additionally, taking into account known magnetomechanical phenomena [18], namely the Villary, Matteuci and Naganka-Honda effects or the phenomenon of austenite transforming into martensite in fatigue loads, it turns out that the change of stress degree in an object will be reflected by a corresponding change of magnetic field [17]. Some of these magnetomechanical phenomena were presented on Fig. 4.

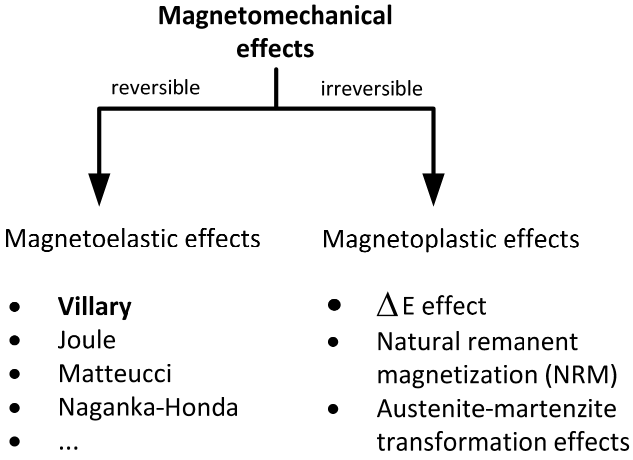


Figure 4: Magnetomechanical phenomena

These magnetomechanical phenomena, especially Villary effect, could be used for estimating mechanical stress in ferromagnetic materials while only relying on the Earth's weak natural magnetic field. It has been proven that there exists the possibility of assessing mechanical stress while relying only on the intensity of changes of the object's own magnetic field which is generated around it [17]. Observing qualitative and quantitative changes in the eigen magnetic field it is also possible to find the crossing of the yield point. The results obtained on the test stand discussed in [19] shows good correlation between strain gauge and magnetic field measurements confirmed the possibility of applying this method in condition monitoring of ferromagnetic constructions. Moreover it occurred that stress assessment in the ferromagnetic objects could be performed remotely. The changes of the magnetic field value are large enough to be measured from the distance – especially fluxgate sensor is suitable for such a purpose.

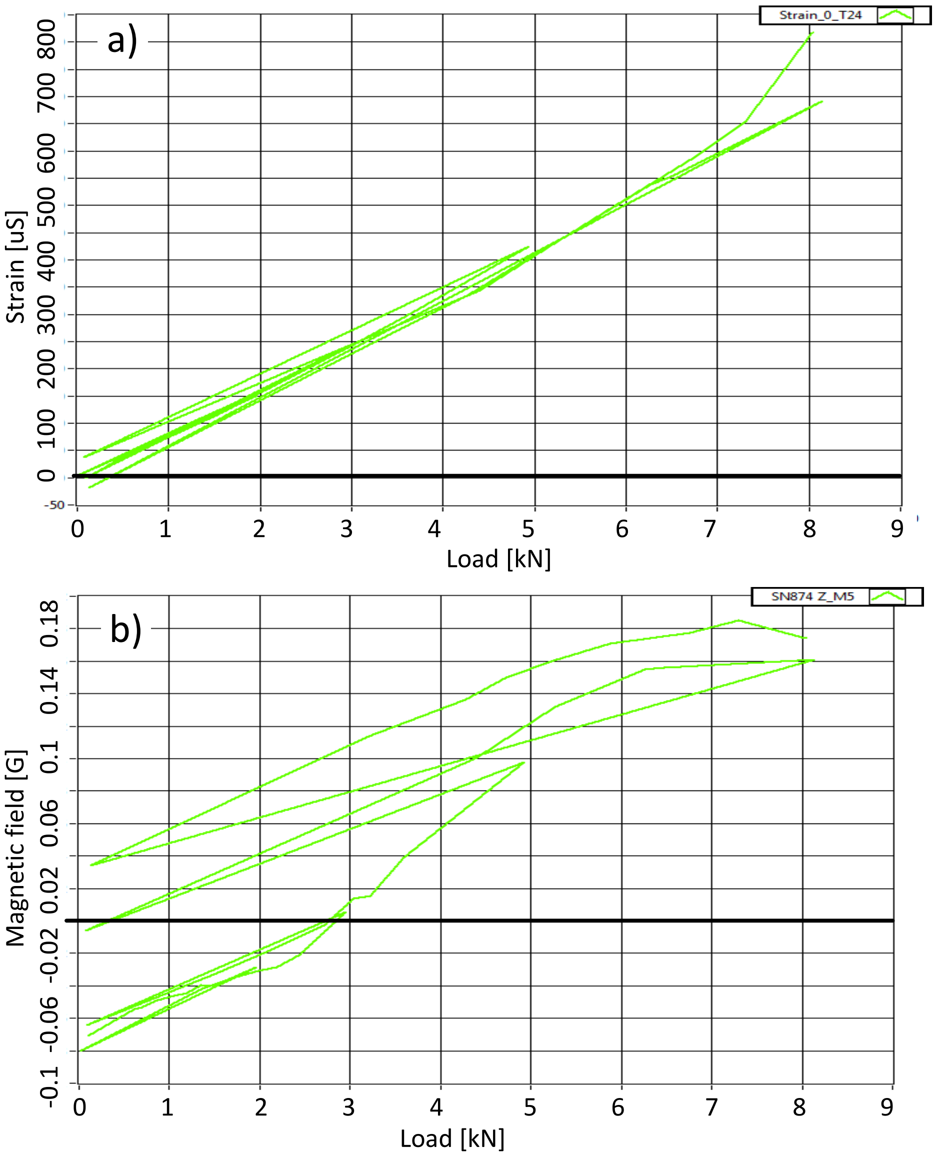


Figure 5: Comparison of strain (a) and magnetic field measurements in the truss member recorded by the system on the test stand [19]

Worth noticing is also a kind of stress memory in the construction visible as a hysteresis on Fig. 5b. This hysteresis is resulting from physical phenomenon of magnetic elasticity, magnetostriction, and their relation to creating and locating the limits of magnetic domains on wall of dislocations in concentration zones of strain intensity. The latter seems to be a very promising way of assessment global stress in the ferromagnetic materials that is currently tested within the system. There are however some drawbacks of this method that should be mentioned. In the algorithm of selecting symptoms one should take into account that the magnetization is dependent not only on stress and its history but also on kind of material, temperature and shape of the object. Moreover, factors like Earth's magnetic field changes connected to the daily and yearly cycles as well as changes of solar activity, and location of the examined object (geographical coordinates), angular position of the structure should also be taken under consideration [17]. The best approach is to use the mathematical model that could take this factors into account.

2.3 Model supported structural health monitoring

Modal analysis is a widely used tool for assessment of technical state of the structures [20]. It allows determination of modal model of structure, consisting of modal frequencies, modal shapes and modal damping. Based on the observation of changes of modal parameters it is possible to infer about changes of technical state of the structure. The main drawback of the method is the requirement of high number of sensors and adequate number of measurement channels in data acquisition system. These two factors with additional requirement of high processing power of computing system make modal analysis difficult to implement in SHM systems working automatically. There are however possibilities to distribute the computations in the system [9].

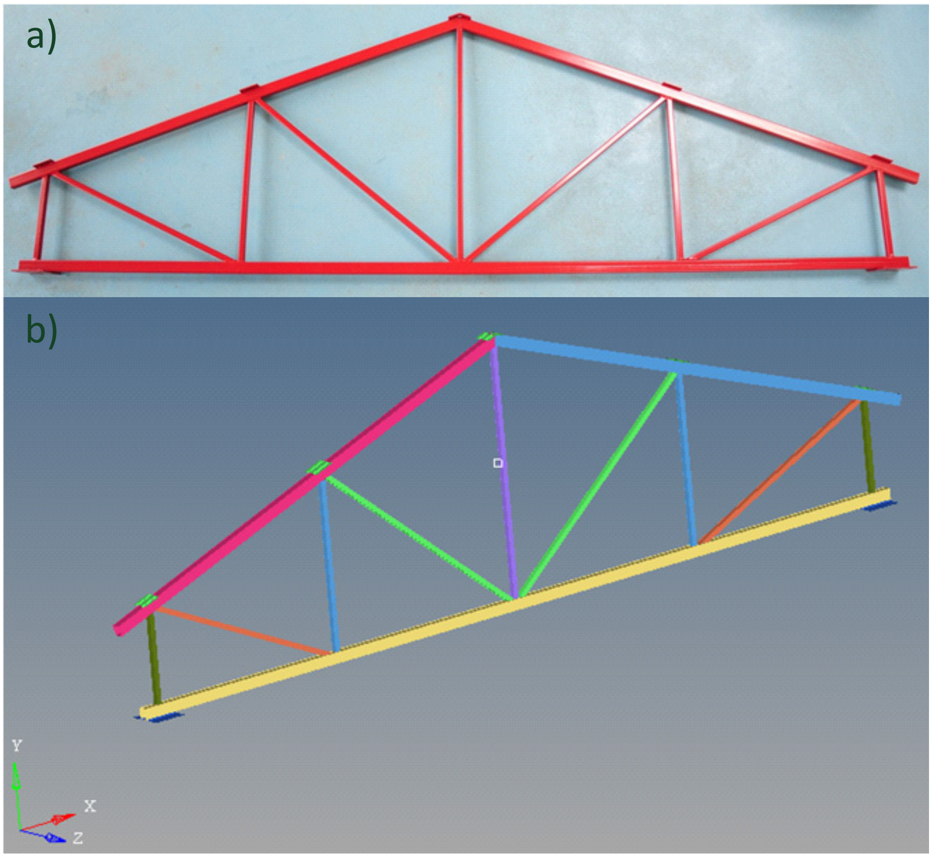
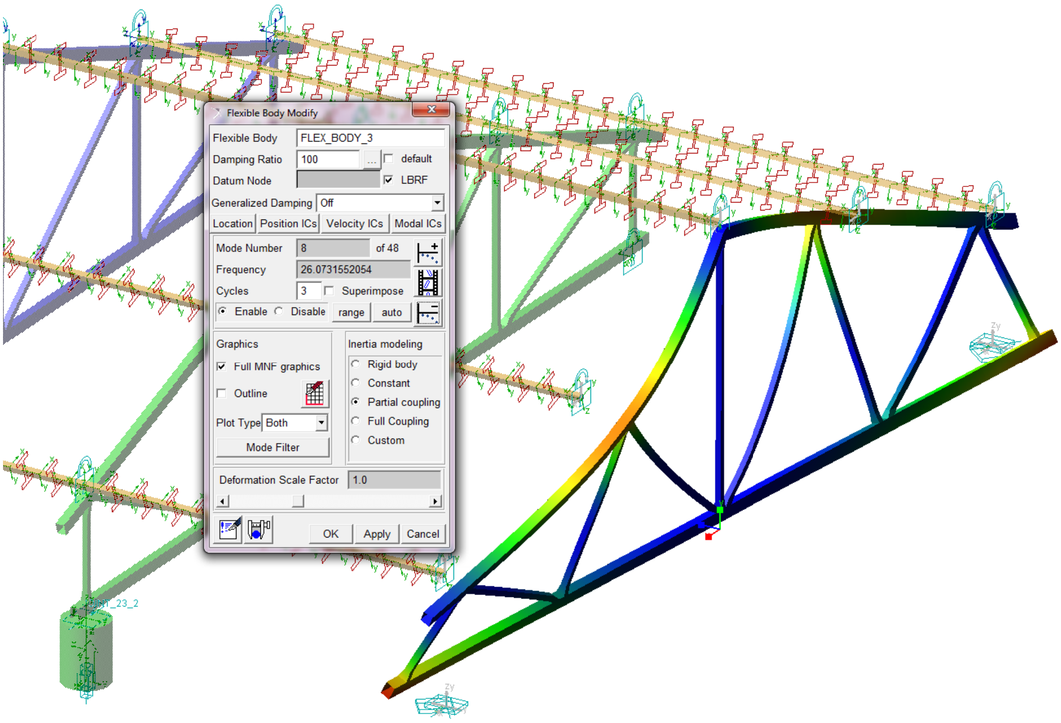


Figure 6: Tested girder (a) and its FE model (b)

Approach proposed in the paper and used in the system assumes usage of verified and validated finite elements numerical model for inferring on causes of changes in the dynamic response of the structure (Fig. 6). Numerical models of the girders, built in Altair HiperWorks environment, were used for selecting the construction elements and joints that are prone to failure. Models were validated on real structures (Fig. 6a), using different types of excitation. Sufficient data were collected for validation and verification process needed for tuning of the finite elements models. In this process different load configurations and environmental conditions were applied to the real structures. This allows for selection of proper placement points of both optic FBG and strain gauges sensors most sensitive to the loading and with biggest stress. These data with conjunction to the FE model were also used for sensor calibration and for assessing stress limits in the stress assessment subsystem of the monitoring system.

Dynamic hybrid model (Fig. 7) was used for finding the modes in the construction most sensitive for selected failures that are dangerous for the construction stability. The monitoring system of the construction is focused on these modes (Fig 8). This allows for reducing the number of acceleration sensors in the measurement subsystem (Fig. 9), simplifying processing algorithms and reducing the amount of processing power needed for computations. Instead of performing modal analysis online by the system it is therefore possible to apply simpler data analysis methods.


Flexible Body Modify
Flexible Body: FLEX_BODY_3
Damping Ratio: 100
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Generalized Damping: Off
Mode Number: 8 of 48
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Cycles: 3
☐ Superimpose
● Enable ○ Disable
Graphics
☑ Full MNF graphics
☐ Outline
Plot Type: Both
Inertia modeling
○ Rigid body
○ Constant
● Partial coupling
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○ Custom
Deformation Scale Factor: 1.0

Figure 7: Hybrid simulation model for assessment changes of mode shapes and frequency under excessive loads

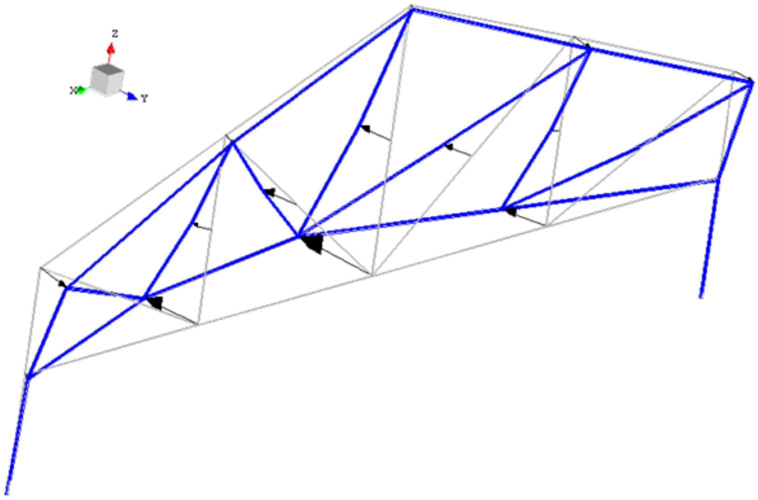

Figure 8: Exemplary mode shape of the real structure of Fig. 5a - 22 Hz.

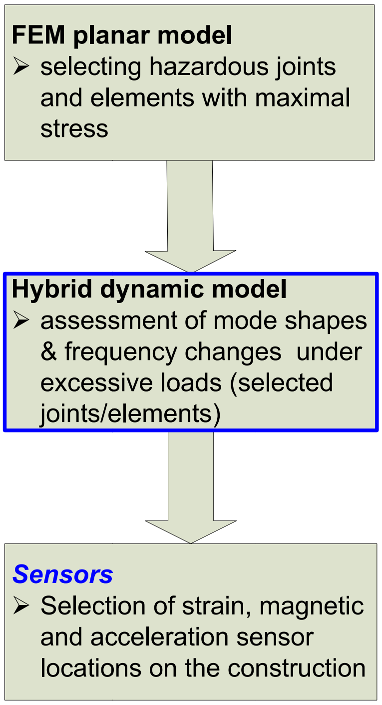

Figure 9: Selection of measurement points on the construction

2.4 Structural health monitoring system implementation and testing

The SHM diagnostic system described above is currently under tests on the laboratory test stand. The test stand described in [19] consists of a steel frame with six hydraulic jacks attached of to it allowing for force application to the model of a steel 3D truss structure that was put inside (Fig. 8). This enables creating different load combinations simulating real word scenarios. Additionally the test stand has, through the usage of piezoelectric stack, the possibility to simulate the additional dynamic loads coming from external sources like e.g. trams or tube passing by, working machines in nearby etc. The truss used on the stand is a scaled model of a construction used typically in civil construction engineering. Current work is focused on finding symptoms of crossing the yield point in selected construction elements.

Figure 8. Test stand with tested truss inside during the experiment

3 Conclusions

This paper presents the concept of a comprehensive diagnostic approach that could increase the reliability of diagnosis of early stages of construction defects. The adaptation of structural health monitoring systems is essential for online assessment of technical state of the infrastructure objects and could limit the possibility of catastrophic disasters with loss of people. Therefore as a solution a monitoring system capable of measuring stresses in the construction based on different available signal sources is being developed and tested. As a source of information data from fibre optic (FBG) as well as classical strain gauges, passive magnetic field and acceleration sensors applied to the construction are considered. Magnetic sensors are used for measuring changes of magnetic field which occurred due to elastic deformation of truss member. As opposed to other methods, it could be done by remote observation of areas of the construction.

The idea of using a passive magnetic method in the diagnostic and prognostic procedures of the construction stress state analysis seems to be an interesting proposal for structure health monitoring systems. An exemplary procedure for construction diagnosis could consist of using a magnetic measurement system for finding critical object's nodes, and then constant monitoring of stress limits that take into account the range of permanent and elastic deformation. This would allow for early detection of threats. SHM data analysis shall take into consideration a series of magneto-mechanical and other phenomena occurring during the operation and also actual magnetization conditions of the object examined in exterior magnetic field (Earth's or derived from adjacent elements). This forces a collaboration with a correspondent mathematical-physical model.

Changes of dynamic properties of structure, detected by developed model based SHM system allows to infer on technical state of object. Changing loads or development of cracks influence modal parameters of monitored structure. As a result of the use of a finite element model it is possible to reduce the number of acceleration sensors thus reducing costs and processing power.

Implementation of the distributed monitoring system makes possible to implement the automation of the analysis, decrease costs related to the maintenance of large scale infrastructure structures and to increase the reliability of a structure

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