Two-year monitoring campaign of a railway truss bridge

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ABSTRACT: A patent-pending integrated system for weighing trains in motion and structural health monitoring of railway truss bridges has been presented. The role of the weigh-in-motion part is to identify dynamic load and provide input for a numerical model of the bridge. The model needs to be well calibrated with data acquired in situ during measuring sessions. Then a damage identification procedure using the Virtual Distortion Method as a tool of model updating can be run in the time domain. The paper describes all components of the system in brief – starting from in-situ data acquisition, ending up with the damage identification algorithm. Results of measuring sessions carried out in 2007 and 2008 on a pioneer in-situ installation of the system are presented. Piezoelectric sensors were used for acquisition of strain responses of rails and bridge members.

1. INTRODUCTION

Growing demand from the institutions responsible for infrastructure maintenance has resulted in a number of practical not just theoretical solutions in the research field of Structural Health Monitoring (SHM) as reported in Uhl et al. (2008). In civil engineering, there is a wide interest from infrastructure administrators in methods enabling efficient operation of structures including a prognosis for remaining lifetime and accompanying guidelines on maintenance.

This paper describes a proposition of a monitoring system for railway truss bridges. The work has been started as a response to the interest in this subject from the Polish Railways. Results presented in this paper include methodology development and field measurements carried out in 2007 and 2008.

The theoretical background for damage identification is the Virtual Distortion Method (VDM) originated by Holnicki-Szulc (2008). Making use of measured responses on the one hand and a numerical model on the other, an inverse problem is solved leading to updating of the numerical model, which results in some damage scenario. Stiffness degradation and loss of mass are regarded as damage parameters. The procedure of identification relies on processing histories of strains in the time domain using gradient-based optimization algorithms.

The measurement part of the problem is realized by piezoelectric sensors, which are supposed to measure strains, unlike in many other SHM applications. The advantage of piezoelectric sensors over strain gauges is easier mounting and extended durability, over fibre optic sensors – price.

2. MONITORING SYSTEM AT A GLANCE

The investigated object is a typical railway truss bridge spanning a channel in Nieporet near Warsaw. There are several hundreds of similar bridges of various spans all over Poland. The bridge, shown in Fig. 1, is made of steel and has a span of 40 m and height of 8 m. There is just one rail track on the bridge so it is not prone to torsion when loaded by a train. Like many other bridges it is just visually inspected once in a few years for maintenance.

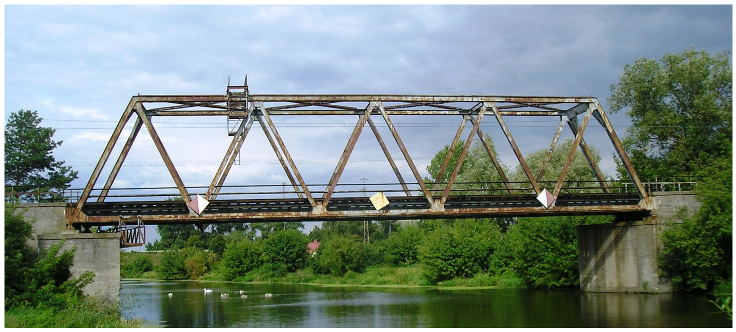

Fig. 1 Investigated railway truss bridge in Nieporet

The patent-pending monitoring system proposed by Adaptronica and Contec (2009) consists of two integrated parts as depicted in Fig. 2. The first part is responsible for weighing of trains in motion, which aims at dynamic load identification. The second part is the actual SHM system applied to the railway truss bridge pictured in Fig. 1.

The idea of weigh in motion (WIM) was reported many years ago, e.g. in the paper by Moses (1979). In the described system it provides a load input for modelling of bridge responses. The idea is somewhat similar to the ambient excitation in the sense of using an existing source, but is different in the sense of measuring the input force. The WIM part is supposed to weigh the passing trains at their actual velocities. It should be mounted in the vicinity of a monitored bridge e.g. 50 m away. This part may also exist on its own to provide information about rail traffic.

The bridge monitoring part assumes a calibrated numerical model regularly supplied with measurement data sent remotely via the Global System for Mobile (GSM) communications. The data include both the load information from the WIM part and the bridge responses to passing trains. By determination of deviations in the measured bridge responses, exceeding a pre-defined threshold value, the damage detection stage is satisfactorily completed. The more advanced stage of damage identification employs a VDM-based numerical analysis, which points out defective elements of the monitored truss structure and quantifies the intensity of damage in such elements. With a record of archived results e.g. 3 year regular monitoring, the structural degradation rate might be assessed and a prognosis of remaining lifetime worked out.

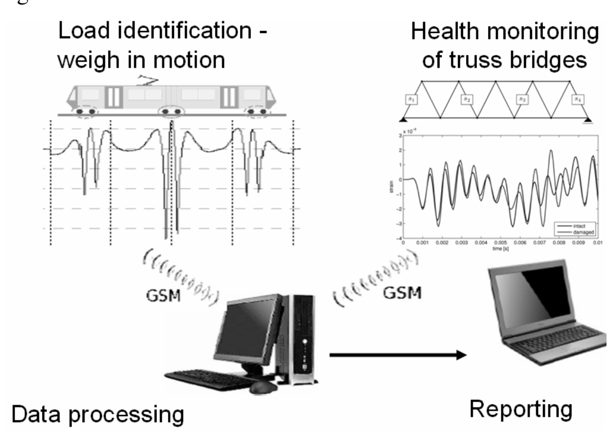

Fig. 2 The integrated monitoring system for railway truss bridges: left – weigh in motion part, right – structural health monitoring part

3. DATA ACQUISITION AND TRANSFER

3.1. Mounted sensors

In Fig. 3 the configuration of all sensors mounted for the WIM and SHM parts of the system is shown.

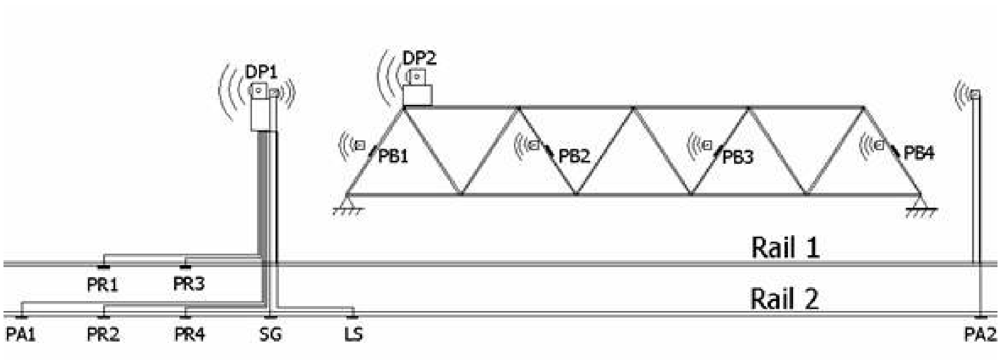

Fig. 3 Layout of sensors mounted for WIM and SHM purposes and scheme of wireless transmission of data: PA – piezosensor for system activation, PR – piezosensor on rail, PB – piezosensor on bridge, SG – strain gauge, LS – laser sensor, DP – data processing unit

There are two types of piezoelectric sensors used – PZT (piezoceramic) and PFC (fibre-based) – mounted on the bottom of rail foots for WIM and on truss elements of the bridge for SHM. A strain gauge was also used for comparison with piezosensor responses. Additionally there was a laser sensor mounted on the rail to monitor its vertical displacements. All types of sensors are pictured in Fig. 4.

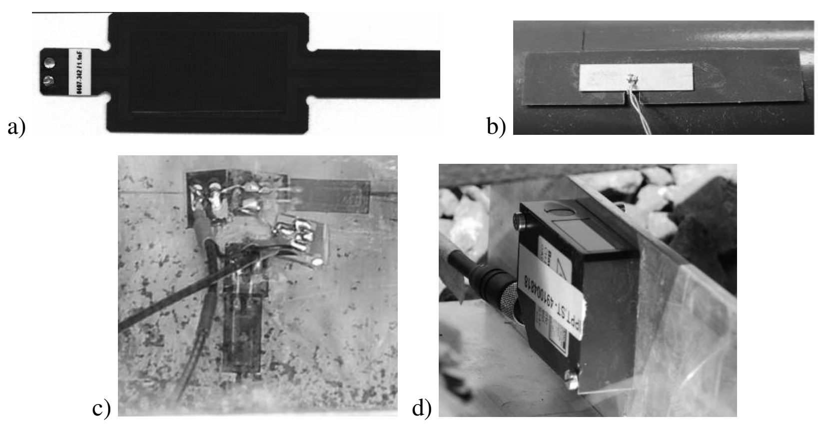

Fig. 4 Types of sensors used: a) PFC, b) PZT, c) strain gauge, d) laser sensor

3.2. Wireless transmission of data

During the measuring sessions carried out in 2007 and 2008, standard co-axial cables were used for the acquisition of WIM and bridge response data. Even though the bridge is a rather small one and the overall (combined for WIM and SHM) number of mounted sensors is less than 12, the use of cables for data acquisition turned out to be very laborious. This has been an incentive to develop a wireless system of data transmission, depicted in Fig. 3.

The idea is to perform the transmission on two levels – in the nearby range and far range. One data processing unit DP1 mounted outside the bridge collects the WIM data via standard cables. Another data processing unit DP2 mounted on the bridge interrogates integrated bridge sensors in order to transfer the SHM data wirelessly in the short-range mode. Then both the WIM and SHM data are independently sent to a remote centre for analysis in the far-range transmission mode using GSM.

4. IDENTIFICATION OF LOADS - WEIGHING IN MOTION

4.1. Measuring sessions

The measuring sessions in 2007 and 2008 were mainly focused on the WIM part of the system. The idea of data acquisition and transfer for the system is schematically shown in Fig. 5.

Piezosensors collect strain responses of the rail due to passage of trains. The responses are then buffered and pre-processed by the in-situ data processing unit DP1 and subsequently sent to a remote server using the far-range transmission mode for further analysis.

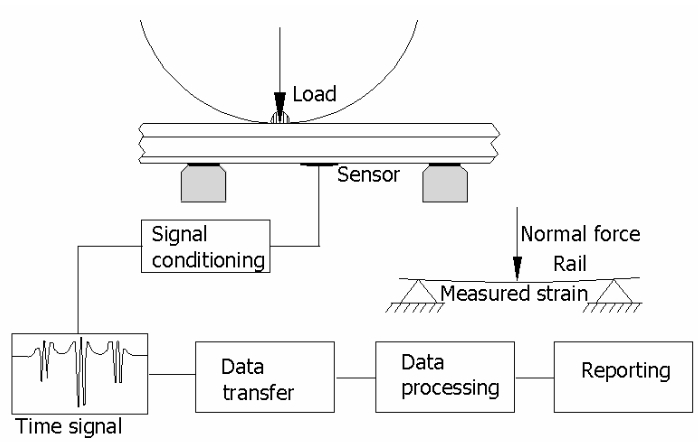

Fig. 5 Data acquisition, transfer and processing in the WIM part of the system

Fig. 6 illustrates a time signal collected by the piezo-sensors during a passage of an 11-car freight train at 40 km/h. The first part of the signal (with higher amplitude) corresponds to a locomotive with three-axle bogies, the rest – to cars with two-axle bogies. The basis for identification of the magnitude of train load are the peak values of the time signal averaged from all WIM sensors. A reference level for load magnitude must be set in a calibration procedure. Train velocity is identified by WIM as well.

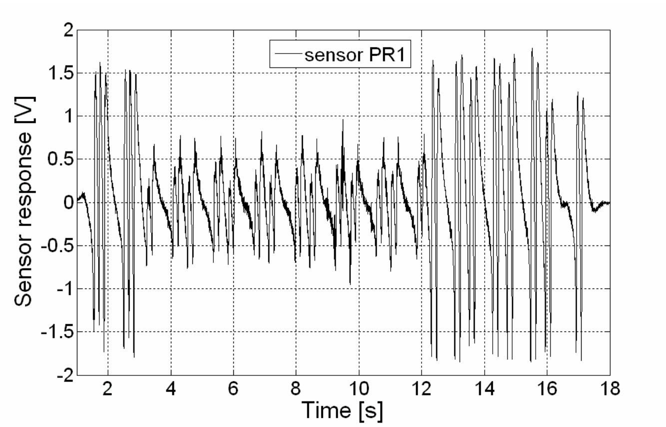

Fig. 6 Time signal collected by a piezosensor during the passage of a freight train

Fig. 7 presents a relation between the mass of cars determined in a quasi-static (at 5 km/h) weighing and the voltage signal captured by piezosensors (at 40 km/h). It can be seen that the trend is linear despite generally poor condition of the railway track in the place of installation of the WIM system.

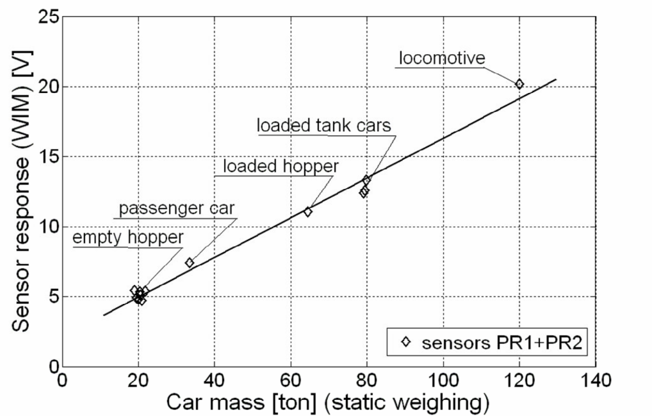

Fig. 7 WIM sensor signals vs. car mass – trend line

4.2. Confrontation with numerical model

A numerical model of rail-sleeper-ground interaction was built in the FE program ADINA to compare numerical and experimental data. Timoshenko beam was used to model the rail and Kelvin-Voigt model to interpret the sleeper-ground behaviour. Vertical forces moving along the rail with constant velocity were applied to simulate train passage as shown in Fig. 8.

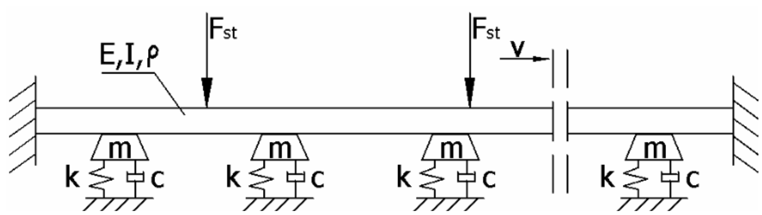

Fig. 8 Model of the rail-sleeper-ground interaction

A comparison between the numerical and experimental results is presented in Fig. 9. Vertical displacements and stresses are displayed for passage of a locomotive. Good conformity of results can be observed.

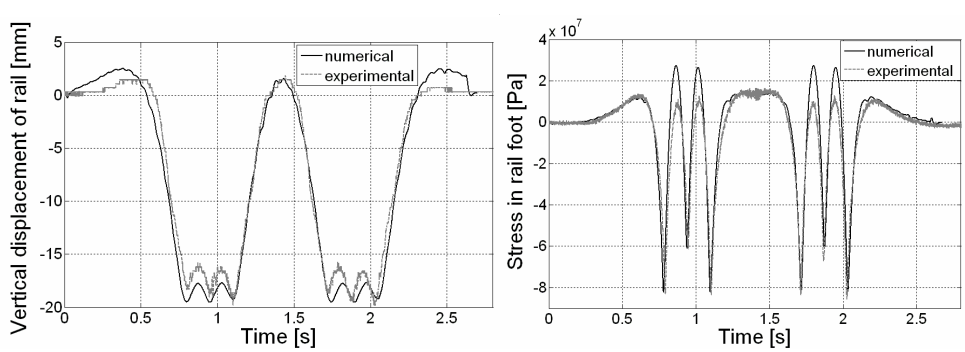

Fig. 9 Numerical vs. experimental results for the WIM part of the system

5. IDENTIFICATION OF DAMAGE

5.1. Virtual Distortion Method

The procedure of damage identification relies on the Virtual Distortion Method (VDM) developed by Holnicki-Szulc (2008) and his research team. The VDM can be classified as a fast method of structural reanalysis, which is quite similar in merits to model updating techniques. The basic idea of VDM is to gather information about internal relations in a skeletal structural system. This is performed by locally introducing unit perturbations e.g. strains and looking at the corresponding response of the whole system. The complete set of inter-relations for a structure, obtained by introducing such perturbations consecutively in each structural member, is called the influence matrix. This matrix contains all mechanical information about the system including boundary conditions, topology, etc. The local perturbations of virtual character, which are called virtual distortions, are introduced to the system in order to effectively model real modifications in the system, e.g. change of cross-sectional area, at small numerical cost. The mathematical problem is limited to the number of modified elements only. With the influence matrix, there is no necessity of rebuilding the stiffness matrix, thus a reanalysis due to modification is quick.

The application of VDM to problems of SHM started by extending the static VDM to a dynamic approach. First results of damage identification in truss structures were reported by Kolakowski et al. (2004). The time-domain approach suffered from considerable computational effort, which was subsequently improved by using a more sophisticated optimization method as described in Kolakowski et al. (2008). A special case of the algorithm is limited to harmonic excitation as proposed by Swiercz et al. (2008). With this excitation the problem becomes quasi-static and can be analyzed in the frequency domain by examining the amplitudes of responses only.

5.2. Identification procedure

The idea of damage identification in truss structures will be now briefly presented. It is assumed that linear systems are analyzed and structural damage of a truss element is modelled with two parameters – degradation of stiffness and/or loss of mass. Consequently two types of virtual distortions have to be considered – one modelling stiffness and related to static response of a structure, the other modelling mass and inherently related to dynamic responses.

With the influence matrix storing strain responses D, a superposition of initial strain response ε^L due to external load and residual strain response ε^R due to structural modification can be performed as follows:

$$\varepsilon = \varepsilon^L + \varepsilon^R = \varepsilon^L + D\varepsilon^0 \tag{1}$$

where: ε – total strain, ε^0 – virtual distortion modelling stiffness modifications.

The internal forces in truss members due to real modification of stiffness e.g. of Young's modulus and due to introduction of virtual distortion ε^0 supposed to model this fact are the following:

$$\begin{aligned} P &= E'A\varepsilon \\ P &= EA\left(\varepsilon - \varepsilon^0\right) \end{aligned} \tag{2}$$

where: E – initial Young's modulus, E' – modified Young's modulus, A – cross-sectional area.

The static postulate of VDM says that the forces in eq. (2) be equal, which leads to the relation for the coefficient of modification μ:

$$\mu = \frac{E'}{E} = \frac{\varepsilon - \varepsilon^0}{\varepsilon} \tag{3}$$

With the influence matrix storing displacement responses B, similarly to eq. (1) we can establish relations for displacements or accelerations:

$$u = u^L + u^R = u^L + Bf^0 \tag{4}$$

where: u – total displacement, f^0 – virtual distortion modelling mass modifications.

Equations of motion of an undamped system with real modification of mass and with virtual distortions f^0 supposed to model this fact have the form:

$$\begin{aligned} M'\tfrac{d^2}{dt^2}u + Ku = f \\ M\tfrac{d^2}{dt^2}u + Ku = f + f^0 \end{aligned} \tag{5}$$

where: M' – modified mass matrix, M – initial mass matrix, K – stiffness matrix.

The dynamic postulate of VDM requires that the inertia forces and accelerations be equal, yielding:

$$(M'-M)\tfrac{d^2}{dt^2}u + f^0 = \Delta M\tfrac{d^2}{dt^2}u + f^0 = 0 \tag{6}$$

If both damage degradation and mass loss are considered, eq. (3) and (6) constitute a set of equations which should be solved for the stiffness-modelling distortions ε^0 and mass-modelling distortions f^0.

In the identification process, a minimum of the following objective function is sought:

$$F(\mu) = \left(\frac{\varepsilon - \varepsilon^M}{\varepsilon^M}\right)^2 \tag{7}$$

where: ε^M – measured strain.

The modification coefficient has to be bounded in the range <0,1> in order to consider structural damage. Gradient of the function (7) with respect to the design variable μ is calculated using the chain rule of differentiation. Partial derivatives of ε^0 and f^0 with respect to μ are computed by both side differentiation of the set of equations (3) and (6), which produces the same left-hand side matrix as in the primary set (3) and (6). The design variable μ is updated in iterations by an optimization routine e.g. simple steepest descent as in Kolakowski et al. (2004) or advanced Levenberg-Marquardt as in Kolakowski et al. (2008).

The described model updating process effectively solves an inverse problem of parameter identification relying on strain measurements and gradient-based optimization methods.

5.3. Numerical model of the bridge

The WIM part of the system provides input for the SHM part. Knowing the dynamic load exerted on rails by a passing train, one can perform time-domain VDM-based dynamic analysis as explained in 5.2. With a numerical model of the bridge, schematically depicted in Fig. 10 we can determine responses of the bridge excited by a passing train using the Newmark method of integration of equations of motion.

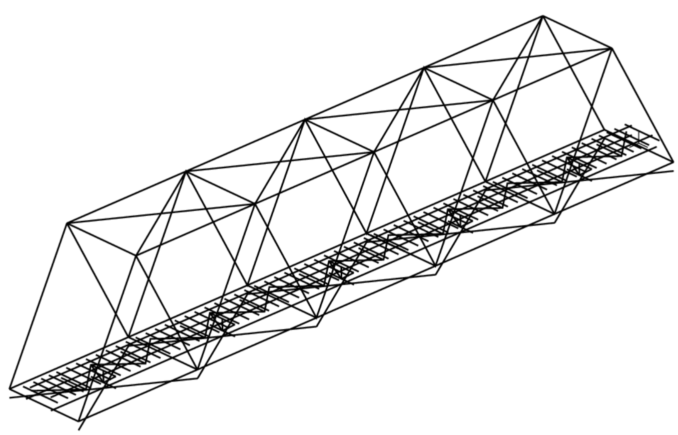

Fig. 10 3D model of the bridge built in ADINA

The model has been built using technical documentation made available by Polish Railways. The stage of calibration of the model to experimental responses is still a challenging task to be accomplished. Once this has been done, the identification procedure described in 5.2 can be run.

In fact, the justification of building the model in a commercial FE program ADINA is a user-friendly way of visualizing it. Our in-house code lacks a professional post-processor. The mechanical characteristics of the bridge will be contained in the influence matrices, which are series of responses due to local perturbations calculated with the ADINA model. If the matrices are extracted from the commercial program, our in-house software will be used solely for identification purposes.

6. CONCLUSIONS

The presented integrated system seems to be capable of meeting two needs of the administrator of the railway infrastructure i.e. monitoring of rail traffic (especially of freight trains) by the WIM part and monitoring of current health of railway truss bridges by the combined WIM and SHM parts. Some results from the pioneer installation of the system in Nieporet have been demonstrated. Further in-situ measurements are envisaged in the future. The stage of model calibration and running the identification algorithm on experimental data will be faced soon.

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