This paper provides view of current trends in the field of bridges testing and monitoring. It describes what is role of bridge structure testing in the management of the construction industry and bridge infrastructure.

1. Introduction

Realistic modelling of the bridges behavior for dynamic analysis, determining and control relevant parameters for evaluation new and existing bridges via dynamic diagnosis of bridges is considered. Full–scale dynamic testing gives very useful information for modelling and assessment of real bridge conditions. This information consists of observed quantities obtained by experimental tests, theoretical analysis and numerical computation and their comparison. Nowadays the important role in the control of the bridge structures plays monitoring of the structural parameters during normal bridge traffic on bridge (relative change of eigen–frequencies, damping parameters, fatigue parameters, vibration effective amplitudes value in time histories, etc.). Some results from bridge forced vibration tests (vibration is artificially induced) and also from bridge monitoring ambient vibration tests (input excitation is not under the control of the test engineer) are also given.

2. Theoretical and numerical models of bridges structure

Mathematical models of real bridge structures usually involve assumptions in modelling, such as mechanisms of flexibility, energy dissipation, inertia and boundary conditions [1,2,3]. In the cases, of the complicated and sophisticated numerical models, it is useful to develop an appropriate model with realistic prediction of their dynamic response. It will lead, after comparison of the experimental results and theoretical predictions, to realistic and more economical designs.

To create relevant analytical models there is useful application of Experimental Modal Analysis (EMA) utilizing mainly engine frequencies, frequency response functions and damping parameters of the tested bridge. But EMA real conditions are too restrictive for performance of such dynamic test and sometimes it is impossible for performance bridge long time monitoring. In these cases, is possible use the Operational Modal Analysis procedure which enable to carry out monitoring measurements without interrupting bridge service. A brief but well presented review of testing methods for bridges explaining their advantages and limitations was presented e.g. by Salawu and Williams [1].

The bridge dynamic analysis programs are common available and computational problems are not complicated to solve. Lot of FEM software packages are used in this field mainly for structures
modal analysis and dynamic response of bridges (ANSYS Civil FEM Bridge, BRASS, BRIDGES BridgeSoft, BRIGADES (ABAQUS), ADINA, DYNsolv, LUSAS, etc.)

3. Full–scale dynamic loading tests of bridges and monitoring

Full–scale dynamic testing gives very useful information for modelling and assessment of real bridge conditions. In many countries the assumption of putting the bridges and viaducts into operation is performance of static and dynamic tests, which aim is to proof and to confirm the quality (standards criteria, serviceability, safety limit states, etc.) of these structures. For this purpose the tests completion are given by technical standards (in Slovakia by STN 73 6209). From static or dynamic test results is possible to calibrate of a bridge analytical model. Also test results can be utilize as basic condition for a bridge health monitoring program.

3.1 Test procedures

As an example there is described highway bridges test procedure according to STN 73 6209. Highway bridges mainly are tested dynamically (Dynamic loading test – DLT) by the passage of single, fully loaded, multi–axles lorries. The gross weight of the testing vehicles usually lies near the legal limit which is established by regulations. Locomotives are used in the case of railway bridges. Normal traffic flow can also be used for both highway and railway bridges. Dynamic calculations, mainly for the dynamic bridge response caused by individual vehicles, e.g. four–axle lorries or locomotives, are carried out before the dynamic tests. The testing vehicle is driven at a constant speed along the bridge and always in the same direction. The tests begin with a vehicle speed of \( c = 5 \text{ km/h} \) which is increased after each passage in steps of \( 5 \text{ km/h} \), up to the maximum achievable speed [3]. If a static test is not performed before the dynamic tests, the bridge deflection caused by vehicle travelling at a speed \( c = 5 \text{ km/h} \) can be considered to present the static deflection \( w_s \) with sufficient accuracy. In the case of highway bridges, the tests on the undisturbed bridges pavement are repeated with a plank or standard obstacle placed across the roadway (the plank has approximate dimensions \( 50 \times 300 \times 5000 \text{ mm} \); the cross section of the standard obstacle is a cylindrical sector, of height \( 60 \text{ mm} \) and chord length \( 500 \text{ mm} \)). Pay load, tyres and tyre pressure are kept the same, so it can be assumed that the dynamic properties of the vehicle remain approximately constant during the tests of highway bridges.

Pulse forces, produced by the ignition of pulse rocket engines (PRE) are during DLT used, too. Harmonically variable forces, produced by vibration exciters and the free vibrations of the bridge are also measured. The main reason for performance of the DLT is to evaluate dynamic parameters of the bridge. These parameters are then used for dynamic model calibration or as a reference to monitor changes in structural performance. Monitoring of the bridges performed on the same bridge during the several years can point to e.g. change frequency (\( f \)) damping (\( \eta \)) and \( (w_{rms}) \) displacement amplitude values. As an example bridge case study experimental analysis results are detailed description in [3,4]. Usually greater changes in dynamic parameters obtained in dynamic tests made in the same conditions are related with structural modifications and not with ambient changes.

There are also the so–called proof–loading tests for checking if the construction of the bridge has been performed according to the design. These tests (DLT) comprise evaluation of the dynamic loading factor (DLF – STN standard value by designer) and dynamic amplification factor (DAF – from DLT), greater than 1: the amount by which the static effects are increased by bridge–vehicle interaction contribution. Several countries have standards to obtain this coefficient in a normalized way (Switzerland, Canada, USA, U.K., Spain, France, Germany, India, Czech Republic, and Slovakia).

Nowadays, there is an another group of dynamic tests focused to the analysis of the effects of traffic in the fatigue behaviour (experimental stress–spectra in main structural elements) or related to the weigh–in–motion (WIM) techniques where the dynamic response of the bridge is use to obtain the characteristic (gross weight, axle weight and spacing, distance between vehicles, etc.) of
3.2 Data acquisition and recording

Dynamic deflections are measured at the characteristic point of the bridge, which is normally at the mid-span. The time histories of the response of the bridge structure at this point, in the horizontal and vertical directions, are recorded. In many cases, deflections are measured at additional points along the super-structure. In addition to the dynamic deflections, other important parameters are measured: magnitude and time history of excitation forces, speed of the loading vehicles, wind velocity, temperature of the structure and ambient air, etc.

At present, inductive displacement transducers – IDT mounted at the bridge parapet, are used to monitor displacement amplitudes time history during standard dynamic tests of bridges. Recorded displacement amplitudes time history contains both static and dynamic components of the bridge response due to moving load. The measured baseline is provided by an invar wire (max 30 m), stretched between the measuring points of the structure and a fixed reference point under the bridge. The application IDT for the dynamic loading factors assessing is possible by using filtering techniques to extract the static component from displacement time histories. When the main measured cross section is situated over water (e.g. where the bridge crosses a river, lake, bay, etc.) the displacement transducers are usually replaced by accelerometers, velocity–type transducers (recorded acceleration amplitudes time history contains dynamic part of the bridge response) or strain gauges (recorded strain amplitudes time history contains both static and dynamic components of the bridge response due to moving load).

The signals from the used pick–ups are amplified and filtered by the signal amplifiers and low–band pass filters, and are then recorded (by portable notebook (PC) with relevant software (DISYS, DAS 16, NI, PULSE BK, etc.) and hardware facilities.

The recorded signals are usually analysed in laboratory conditions or preferably in situ, using amplitude, frequency and amplitude–phase analysis, by the method of spectral or correlation analysis using frequency analyzer (e.g. Brüel–Kjaer 3550, BK 3560 PULSE, Ono–Sokki CF 920) connected to computer (PC/Pentium) with relevant software.

The transmission of signals from measurement devices to the recording system via special cables with low noise to signal ratio is used. Eliminate the need for costly and prohibitive wiring by taking advantage of the wireless sensor network (WSN) platform for distributed measurement applications such as bridge structural health monitoring. The WSN platform simplifies remote monitoring applications and delivers low–power, reliable measurement nodes that feature industrial certifications and local control capabilities. The quick–setup wireless sensor network can be used to implement a stand–alone remote monitoring system or easily integrate with existing PC and real–time–based measurement and control systems (e.g. NI WSN, BK PULSE WSN), see Fig.1.

3.3 Data processing

The experimental analysis is usually carried out in the laboratory. The vibrations induced in the structure by the lorries crossing the bridge, are analyzed in order to quantify and compare the effects of the different types of runs that, with different velocities, crossed the viaduct during the tests. For the analysis of the levels of vibration, the accelerations, recorded when lorries crossed the viaduct bridge were processed with the following operations:

- removal of offset and linear trends;
- digital filtering with a low–pass Butterworth filter with a cut frequency, e.g. of 150 Hz and with a high–pass Butterworth filter with a cut frequency of 0.5 Hz;
- evaluation of maximum and R.M.S. value of acceleration amplitudes;
- double integration of the accelerations to displacements and evaluation of their maximum and R.M.S. values. The maximum displacements value is mainly used for calculations of the DAF.
From the measured time histories of the bridge response and free vibration, the following information can also be obtained:

- the frequency of one or more modes of the loaded and unloaded bridge;
- damping of the natural vibration, dominant in free decay;
- critical damping coefficient or percentage of critical damping via of the 3dB band with method and curve fitting techniques;
- the dynamic coefficient – dynamic amplification factor (DAF) and its dependence on vehicle speed;
- the magnitude of dynamic and static deflections as well as stresses in certain important parts of the bridge structure;
- time history amplitudes and their classification by one of the classification methods (e.g. rain–flow classification method).

3.4 Bridges dynamic parameters monitoring

Long term observation is discussed in literature [9, 10, 11]. Dynamic methods, also used by other authors [12, 13, 14], were applied to correlate relative changes of material frequencies and damping with carrying capacity. It was found that the monitoring techniques used gave an early indication of incipient deterioration. It has been the scope of monitoring tests to evaluate whether the relative change of well–defined natural frequencies or the change of the corresponding damping and the change of RMS value of the displacements amplitude of the bridge vibration observed by traffic loading can be used to give an overall indication of deterioration or crack formation. The monitoring technique based on measurement of the time history of the bridge vibration due to regular traffic is not meant to give detailed information but to be a technique simple to use to desire whether more detailed methods should be used.

4. Case studies

4.1 Lafrancony motorway bridge over the Danube DLT

The dynamic response behaviour of a prestressed concrete seven span highway bridge (761.0 m long) in Bratislava [3] was examined as a part of the static and dynamic loading tests (DLT) according to standard [15]. In this investigation, a structural measuring technique using vehicle–induced vibrations as well as forced vibrations induced by the rocket engines was developed for full–scale testing of the bridges. The data yielded the dynamic characteristics of the bridge, e.g. natural frequencies $f(j)$, mode shapes, dynamic amplification factor $\delta_{OBS}$ (DAF $\rightarrow \delta_{OBS} = w_{max} / w_x$) and the damping of the structure ($\nu$). The obtained dynamic characteristics were compared with the numerical computed data.

The main bridge structure is composed of seven span continuous beams with one frame pier (P3). Other supports are formed by seven massive piers. The total length of the bridge is 761.0 m with spans 83.0 m + 174.0 m + 172.0 m + 4 x 83.0 m. The highway bridge consists of two independent bridges (left and right bridge) with three traffic lanes each (e.g. three in each bridge for one direction only) and sidewalks on both sides. The bridge longitudinal section is shown in Fig.2.
The test programme included field measurements using the instrumentation described in [3] so as to ensure coverage of entire possible range of vibration. The vibration amplitudes were investigated and recorded in 18 selected points. The time history of vertical as well as horizontal vibration has been registered by accelerometers (BK–8306) in the 2nd and the 3rd span of the bridge in the other spans by inductive displacement transducer (BOSCH), range 40 mm. Fig. 2 shows position of the accelerometers A1–A8 and transducers R1–R10.

Output signals from the accelerometers were preamplified and recorded on two PC facilities four–channel portable tape FM recorder (BK–7005). The measuring station for recording accelerometer signals (DSM–1) was situated on the top of the pier No.P3, Fig.2.

The signals from the inductive displacement transducers were recorded simultaneously at the station DSM–2 and DSM–3 by 12–channel portable tape recorder.

Figure 2: Longitudinal section of the Lafrancony motorway bridge.

Figure 3: Examples of amplitude (a), and spectral (b) analyses results. DAF dependence on lorry velocities (c) and calculated and measured natural frequencies comparison (d).
The DAF $\delta_{\text{obs}}$ has been determined using the analogue records obtained from passing vehicle velocities over the bridge by computer PC via Disys, and DAS 16 software pocket. The frequency response spectrum has been obtained also by using two–channel real time analyzer BK–2032 in the frequency range $0 \div 10$ Hz. This output signal in the form of Fourier frequency spectrum (power spectrum) was recorded by computer and by digital recorder (BK–7400) and plotted by $x$–$y$ recorder BK–2308. The vibration ambientability has been investigated by means of the correlation analysis and spectral analysis in order to obtain cross correlation functions $R_{xy}(t)$ and coherence function $\gamma_{xy}(f)$.

### 4.2 Bridge dynamic parameters monitoring

During the years 1991–2001 Lafranconi bridge over the Danube has been investigated by 24 hours monitoring tests in the summer and the winter time [4]. A theoretical prediction of the bridge behaviour and preliminary dynamic loading tests are reported in [3]. As an example, in the next sections are shortly described bridge monitoring process and results.

#### 4.2.1 Testing procedure and experimental analysis

The test programme included field measurements using the instrumentation is described in [4]. The vibration amplitudes were investigated and recorded in selected points of the second (174,0 m) and the third span (172,0 m). The time history of vertical vibration has been recorded by accelerometers (BK–8306) at points A1, A2, A5, A6 on each independent bridge (Fig.2) in the same position as were situated during DLT [3].

Output signals from accelerometers were preamplified and recorded by portable notebook computer (PC) with special software (DISYS) and hardware facilities for 24 hours continuing test.

The experimental analysis has been carried out in the laboratory of the Department of Structural Mechanics U.T.C. Zilina. The records obtained in the bridge monitoring tests were investigated by using frequency analyser BK–2034 and mentioned PC facilities. Fig.4 shows power spectral densities (PSD) as an example of the spectral analysis of the monitoring test performed in August, 1994. The damping parameter (D–critical damping coefficient) was found by means of the 3dB bandwith method and curve fitting techniques. The amplitude analysis has been used to obtain RMS amplitude value of the bridge vibrations during the monitoring tests.

Results giving frequency and damping for lowest natural frequency in bending and RMS amplitude value from the monitoring tests of the bridges during whole measuring period are shown in Fig.5. A 2.7% change in frequency is observed during a year (summer–winter) but it is systematic from one year to the next and is partly due to changes in ambient temperature. By measuring the frequency at the same time of year the changes from year to year are small and non–systematic and correspond to a coefficient of variation of about 0.01. This may be considered negligible compared with the changes in natural frequency of about 30% corresponding to advanced deterioration observed in [11]. There is not the same systematic change of damping and scattering of results is big. What causes these changes is not clarified. There are changes in the temperature during the day. This may give changes in length of bridge which can influence support conditions and damping. Wind speed, water level, ambient relative humidity and temperature gradients through the deck, transport in the bridge deck, in particular at the surface, and may thereby also change damping [14].

There is a difference of the displacement amplitude RMS value measured in May 1991 in comparison with other measurements results. It was maybe caused by both–side motor traffic flows on the left bridge. All the following measurements were performed in conditions of the one side traffic flow on each of the both Lafranconi bridges. The changes of the amplitude RMS value are caused mainly by changes of the regular motor traffic intensity. The bridge including multispans junctions is fully described in [2].
5. Experimental finding and future study

There has been a considerable amount of research conducted in the fields of bridge dynamic. A review of the analytical and experimental findings [e.g.1,2,3,7,9,10,12,14] has suggested the following conclusions:

1. A lot of experimental findings proved that the dynamic amplification factor (DAF) is related to the fundamental frequency of the highway bridge. Common commercial vehicles moving on bridges have fundamental frequencies in the range of 2 – 5 Hz, corresponding to the resonant frequencies of highway and motorway bridges. It can cause resonances effects during the common performance of the bridges.

2. Analytical and numerical models cannot reliable evaluate the DAF for bridge with many specific mechanical input parameters because of difficulties to model them without experimental proving.

3. During bridge dynamic loading tests, the pickups position on a bridge cross section can gives an unreliable experimental value of the DAF.

4. Full–scale testing under traffic loading is the only economical and practical way to evaluate the DLF with reasonable confidence. It is also a reliable method for determining bridge structural dynamic properties and can be also useful for inspection purposes [2].

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