sciendo

Studia Geotechnica et Mechanica, 2020; 42(4): 291–296

Research Article

Open Access

Jan Bień, Mieszko Kużawa*

Dynamic Tests in Bridge Health Monitoring

https://doi.org/10.2478/sgem-2019-0045
received January 7, 2020; accepted March 19, 2020.

Abstract: Dynamic tests are one of the most significant diagnostic procedures applied in Bridge Health Monitoring in many countries. The paper presents a proposal of unified classification of the bridge dynamic tests together with review of the testing methods, including tests under designed and controlled loads, arranged short-term tests under normal traffic loads as well as permanent dynamic monitoring by means of built-in gauges mounted on a structure. Classification of bridge dynamic tests is proposed taking into account various types of vibration excitation methods, measured parameters and possible applications of obtained results in the Bridge Health Monitoring. General rules and procedures of bridge dynamic tests are described and discussed.

Keywords: Bridge; dynamic tests; bridge condition; Bridge Health Monitoring.

1 Introduction

Bridge Health Monitoring (BHM) usually refers to the process of implementing a damage detection and characterization strategy for bridge structures management.[1–7] Here, damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance.

Process of BHM can be generally defined as an act of acquiring, processing, communicating and archiving information about the structure actions and the actions' effects on a structure over a given period of time.[8–10]

Procedures of Bridge Health Monitoring can be divided into two main categories (Figure 1):

– load-independent procedures, comprising of regular as well as irregular (special) inspections based on visual examination and results of the non-destructive testing (NDT) and/or semi-destructive testing (SDT),
– load-dependent procedures, including tests under controlled loads as well as short- and long-term monitoring under normal traffic and environmental loads (wind, earthquake, etc.).

Load-dependent dynamic tests play a very important role in BHM, because bridge structures are exposed to various dynamic loads, for example, moving live loads, time varying wind loads and so on. The dynamic effects are taken into account while designing bridges and play an important role as one of the basic structure performance indicators during the whole lifetime. The results of the bridge dynamic monitoring and analyses carried out for many years offer valuable information for structure health assessment and bridge management.

Predefined dynamic tests under controlled loads (proof load tests) are typically applied before opening a new bridge structure to traffic or after completing major rehabilitation works. Short- and long-term monitoring is executed under ambient traffic loads and environmental impacts during operation of a bridge. All dynamic tests are based on transducers for sensing physical quantities, programmable electronic equipment for acquiring, processing and communicating data and algorithms that define how data acquisition, processing and communication is performed. Proof load tests and short-term monitoring (24 hours to few days) are usually executed by means of temporally installed sensors, while the long-term monitoring requires permanently mounted system.

The load-dependent monitoring procedures, based on dynamic tests, involve the observation of a bridge structure over time using periodically sampled response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the analysis of these features to determine the current state of structure health. For long-term monitoring, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments.

***Corresponding author: Mieszko Kużawa,** Department of Civil Engineering, Wroclaw University of Science and Technology, Poland, E-mail: mieszko.kuzawa@pwr.edu.pl
Jan Bień, Department of Civil Engineering, Wroclaw University of Science and Technology, Poland

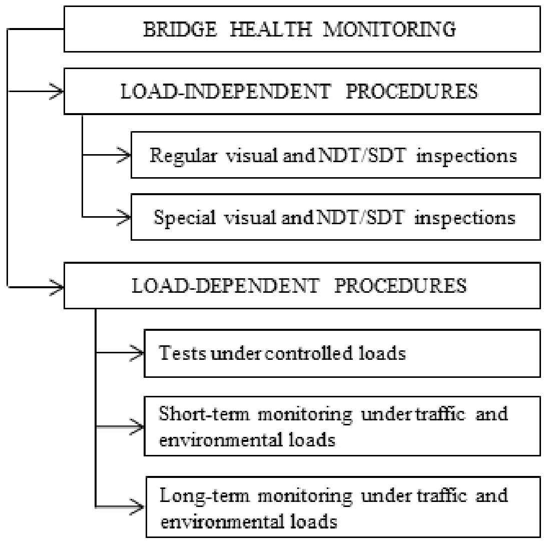

Figure 1: Basic procedures in Bridge Health Monitoring.

2 Classification of bridge dynamic tests

Systematics of bridge dynamic tests considering various methods of structure vibration excitation, the measured and analyzed parameters as well as possibilities of their applications in Bridge Health Monitoring are presented in Figure 2. Taking into account the types of structure vibration excitation, three main groups of bridge dynamic tests can be distinguished:[11–15,25]

– ambient vibration tests under dynamic loads caused by special vehicles or regular traffic as well as vibrations initiated by environmental loads (e.g., wind, earthquakes);
– forced vibration tests performed by means of special exciters (mechanical, hydraulic, etc.) with controlled excitation parameters – placed on the structure;
– free vibration tests achieved by means of special techniques like applied and suddenly released deflection, single impulse load, stopping vehicle and so on.

For the observation of bridge structure reactions to traffic loads and other influences as well as for bridge performance and health monitoring, the following physical quantities are usually measured:[1–10,13,15,25]

– linear and angular displacements,
– strain and stress level and its spatial distribution in a structure,
– vibration velocities and accelerations,
– forces in bearing and cables,
– crack opening changes.

On the basis of the measured values, the following structure dynamic parameters are typically calculated and analyzed (Figure 2):

– Dynamic Amplification Factors (DAF),
– vibration mode shapes, frequencies and amplitudes,
– damping characteristics.

Table 1: Measuring techniques and sensors used in dynamic tests of bridges.

Physical quantity	Measuring techniques and sensors
Linear displacement	Mechanical sensors
	Inductive sensors
	Vibrating wire sensors
	Capacitive sensors Digital Image Correlation
	Fiber optics sensors
	Laser techniques
	Radar techniques
Angular displacement	Inclinometers
	Fiber optics sensors
	MEMS sensors
Strain/stress	Resistance gauges
	Fiber optics sensors
	Vibrating wire sensors
	MEMS sensors
Vibration velocity and acceleration	Piezoelectric sensors
	Capacitive sensors
	Inertia sensors
	Inductive sensors
	Radar techniques
	Laser techniques
	MEMS sensors
Crack opening	Mechanical sensors
	Inductive sensors
	Fiber optics sensors
	Vibrating wire sensors
Bearing/cables reactions	Resistance gauges
	Piezoelectric sensors
	Vibrating wire sensors

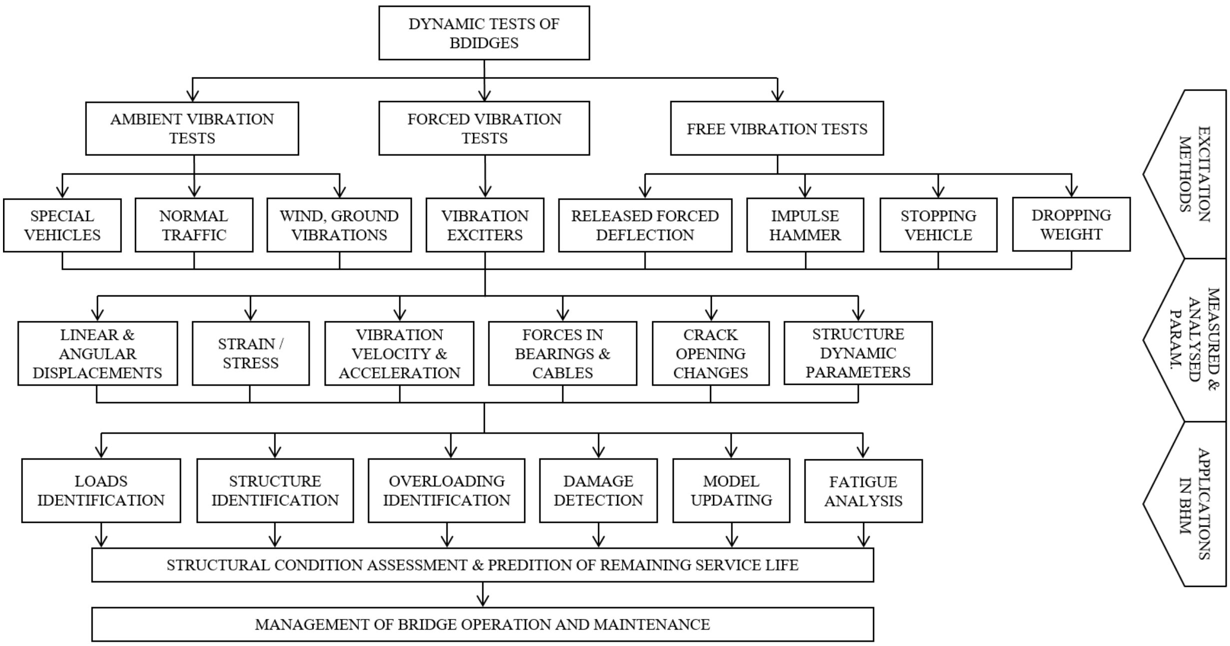

Figure 2: Classification of dynamic tests of bridge structures.

The most popular measuring techniques and types of sensors used in bridge dynamic tests for identification of the physical quantities are presented in Table 1.

In Bridge Health Monitoring process, the results of dynamic tests are generally applied for (Figure 2):

- identification of loads – assessment of the magnitude as well as the spatial and temporal distribution of forces acting on a structure,[3,5,7,16,22,25]
- structural system identification, typically based on dynamic parameters[2,4,6,13,17,25] and focused on structure stiffness, boundary conditions, integrity and so on,
- identification of overloading[13,21,25] by abnormal heavy vehicles, caused by collisions, blast loadings and so on,
- detection and identification of defects by means of analysis of changes of the bridge dynamic parameters,[1,11,14,19]
- updating of numerical model of the structure on the basis of experimental data,[9,13,17–18,25]
- identification of fatigue process based on analysis of stress spectrum in structural elements of the bridge.[9,20]

Generally, the results of bridge dynamic tests create background for assessment of bridge structural condition and for the prediction of the remaining service life of the structure. This information often becomes fundamental for efficient management of bridge operation and maintenance.[3–7]

3 Procedures of bridge dynamic tests

Each dynamic test of bridge has to be designed individually, taking into account specific problems of the observed structure and particular limitations associated with a type of vibration excitation as well as goals of planned tests. Nevertheless, some general steps in design and execution of bridge dynamic tests can be distinguished, as presented in Figure 3.

In the first step, all goals of the dynamic tests should be defined as a basis for design of architecture of a measuring system. In the same time, a theoretical model of the bridge structure is usually created and applied to the calculation of the range of the measured physical quantities and its spatial distribution in a structure. In the next phase, all components of the measuring system should be designed, including type and parameters of sensors, sampling rate, data transmission system, data processing procedures and so on. After detailed design of all components and installation of the whole system on the bridge, the validation procedure should be performed. Experimental values should be compared to the results calculated by means of theoretical model of the structure. Validation process should also confirm that the required precision of measurements is achieved.

In the case of positive results of validation procedure, the testing system can be accepted for application. Some modifications of measuring system as well as theoretical

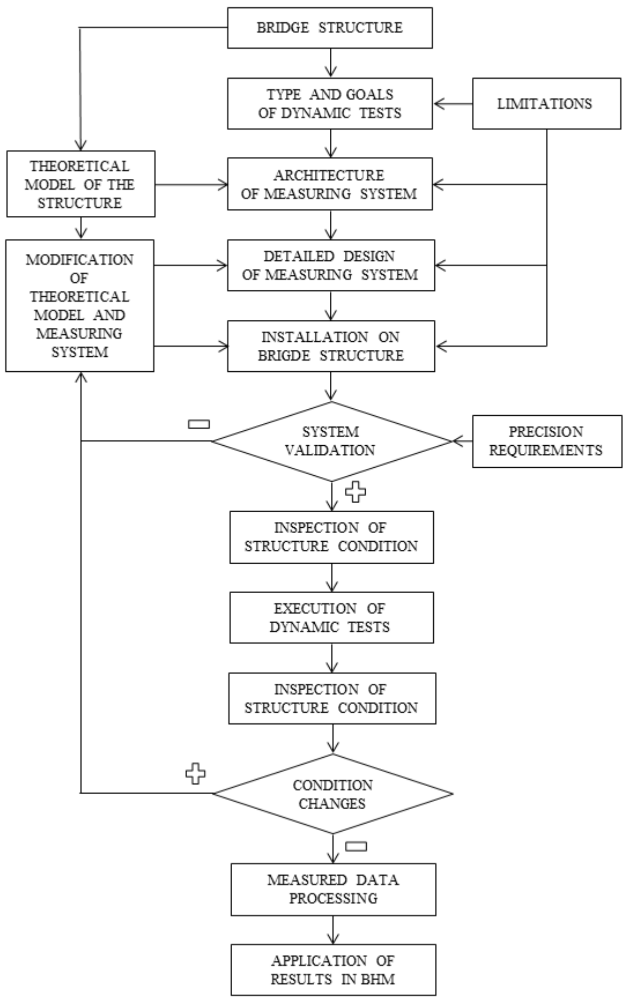

Figure 3: General scheme of design and execution of bridge dynamic tests.

model of the structure are normally required in the situation of problems with system approval.

Execution of the planned dynamic tests should be preceded by detailed inspection of structure condition and the inspection should be repeated after the dynamic tests. All changes of the structure condition before and after the tests (defects) should be included in the theoretical model of the bridge and in the architecture of the measuring system, if needed.

The final step of the bridge dynamic test consists of processing of the output data and their application in the Bridge Health Monitoring practice.

In Poland, the dynamic proof load tests of bridges[17] are standardized in separate but similar codes for steel structures[23] and for concrete structures[24]. The tests are performed under predefined loads in the form of vehicles (trucks or locomotives) as well as special controlled exciters.

Requirements and conditions specified for road and railway bridge dynamic tests are presented in Table 2. The main criterion of bridge selection to preliminary dynamic load tests is theoretical length of the span. Dynamic tests of railway bridges should be obligatorily executed on all concrete structures with spans longer than 15 m and steel structures with spans longer than 21 m. For road bridges, the dynamic tests are required for steel structures with spans longer than 21 m and for concrete structures – for individually selected bridges.

For all types of bridges, the positive results of static loads are required to execute the dynamic tests. During the standard dynamic tests, the loading vehicles are passing through the bridge with a constant speed, starting with the speed 10 km/h. For each consecutive test, the speed is increased by 20 km/h up to the maximum allowable speed v_{max}.

During the tests of concrete road bridges, the artificial bumps of height up to 10 cm can also be used to simulate potential irregularities of the road surface (e.g., potholes).

Short- and long-term dynamic monitoring (see Figure 1) is executed under ambient traffic loads and environmental impacts during the operation of a bridge. During such tests, some maintenance activities are often necessary. It includes mostly:

– modifications or replacement of the measuring system components,
– changes in data transmission network,
– improvements of the bridge theoretical model engaged in analysis of monitoring results,
– corrections of data processing and analysis procedures.

Taking into account the bridge structure excitation method (see Figure 2), two types of groups of dynamic characteristics can be distinguished:

– vibration parameters of the structure subjected to a specific load, mainly special vehicles or normal traffic (simultaneous vibration of the bridge and vehicles), identified during the so called operational tests with ambient excitation,[5,8–10,13,17,20]
– parameters of the vibrating bridge structure itself (modal tests) identified during forced vibration or free vibration tests.[2,12,14,18]

Operational tests usually use typical traffic (vehicles, trains, pedestrians) as the source of excitation to identify the response signal of the structure on the specific dynamic load. Identified parameters of the signal (excited frequencies and operational deflection shapes) give information about the whole structure-vehicle system

Table 2: Requirements for dynamic tests of bridges in Poland.

Characteristics of bridge dynamic tests	Road bridges		Railway bridges	
	concrete	steel	concrete	steel
1. Obligatory proof load tests	structures on investor's or owner's recommendation	with spans longer than 21 m, prototypes, structures with damages, other structures on investor's recommendation	with spans longer than 15 m and other structures on investor's or owner's recommendation	with spans longer than 21 m, prototypes, structures with damages, other structures on investor's recommendation
2. Dynamic loads	trucks or exciters	trucks or exciters	locomotives or exciters	locomotives or exciters
3. Artificial bumps	h = 0,10 m, by v = 0, 6 v_{max}	not specified	not acceptable	
4. Dynamic tests condition	positive results of static tests			
5. Loading vehicles speed	from 10 km/h with step 20 km/h up to allowable speed v_{max}			
6. Measured values	strain, displacement, acceleration, velocity of vibration			
7. Assessment criteria	individually defined by certified research center			

behavior. In case of the use of normal traffic as excitation, the results of operational tests are biased by additional mass of the live load moving along the structure. Results can be more accurate when the following assumptions are fulfilled:

– excitation has to be applied randomly in terms of space and spread on the whole structure,
– excitation has to be random in terms of frequency and lasting, preferably during the whole test.

Modal testing of structure, based on the analysis of the response of the structure on a defined and measured excitation (exciters, special techniques), gives an answer on its natural frequencies, scaled mode-shapes and modal damping coefficients. In this method, applying of excitation do not affect the tested structure, neither by added mass nor by modification of stiffness, meeting the assumption that the obtained results should reflect characteristics and performance of the real bridge structure.

Both kinds of tests offer very useful knowledge, which supports the assessment of serviceability and condition of the structure in the process of bridge health monitoring as a part of Bridge Management Systems.

4 Concluding remarks

Dynamic tests play more and more important role in health monitoring and management of bridge infrastructure (e.g.,[1–9,17,20]). The tests may be carried out both in a permanent way by means of built-in gauges mounted on a structure as well as within systematic inspections and arranged tests of a limited duration with application of external measuring devices.

The main goals of dynamic tests in Bridge Health Monitoring process can be formulated as follows:

– on-line observation of bridge technical condition and serviceability based on predefined performance indicators,
– analysis of changes in structure response to loads focused on detection and identification of defects,
– input values for individual lifetime model for monitored bridge helpful in operation and maintenance planning,
– cognitive analysis of bridge structures for improvement methods of design, modelling and analysis, maintenance, optimization of costs and so on.

References

[1] S.W. Doebling, C.R. Farrar, M.B. Prime, D.W. Shevitz, Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics, A Literature Review, Los Alamos National Laboratory, LA–13070–MS, 1996.

[2] J. Bień, J. Krzyżanowski, P. Rawa, J. Zwolski, "Dynamic Load Tests in Bridge Management", Archives of Civil and Mechanical Engineering, vol. 4, no. 2, pp. 63–78, 2004.

[3] Structural Health Monitoring of Civil Infrastructure Systems (Eds: Karbhari V.M., Ansari F.), CRC Press, 2009.

[4] H. Wenzel, Health Monitoring of Bridges, J. Wiley & Sons Ltd., 2009.

[5] V.M. Karbhari, F. Ansari, Structural Health Monitoring of Civil Infrastructure Systems, CRC Press, 2009.

[6] T. Uhl, "SHM of Civil Structures – methods, tools and applications", 3rd International Conference "Experimental Vibration Analysis for Civil Engineering Structures – EVACES'09", Wrocław, pp. 73–92, 2009.

[7] D. Balageas, C.-P. Fritzen, A. Güemes, Structural Health Monitoring, John Wiley & Sons, 2010.

[8] H. Wenzel, D. Piechler, Ambient Vibration Monitoring, J. Wiley & Sons Ltd, 2005.

[9] S.S. Law, X.Q. Zhu, Damage Models and Algorithms for Assessment of Structures under Operating Conditions, CRC Press, 2009.

[10] R. Helmerich, E. Niederleithinger, Ch. Trela, J. Bień, T. Kamiński, G. Bernardini, "Multi–tool inspection and numerical analysis of an old masonry arch bridge", Structure and Infrastructure Engineering, vol. 8, no. 1, pp. 27–39, 2012.

[11] S.A. Neild, P.D. McFadden, M.S. Williams, "A Review of Time-Frequency Methods for Structural Vibration Analysis", Engineering Structures, no. 25, pp. 713–728, 2003.

[12] W. Skoczyński, J. Krzyżanowski, J. Bień, "New Solutions of Shaker's Supporting Structure Intended to Railway Bridge Testing", In: DAAAM International Scientific Book 2006, Chapter 46, DAAAM International, Vienna, Austria, pp. 569–582, 2006.

[13] A. Cunha, E. Caetano, F. Magalhaes, "Output–Only Dynamic Testing of Bridges and Special Structure", Structural Concrete, vol. 8, no. 2, pp. 67–85, 2007.

[14] J. Zwolski, J. Bień, "Modal analysis of bridge structures by means of Forced Vibration Tests", Journal of Civil Engineering and Management, vol. 17, no. 4, 2011.

[15] D.J. Ewins, Modal Testing: Theory, Practice and Application, Research Studies Press Ltd., Baldock, Hertfordshire, UK, 2000.

[16] K.C. Yap, D.C. Zimmerman, "A Comparative Study of Structural Dynamic Modification and Sensitivity Method Approximation", Mechanical Systems and Signal Processing, vol. 16, no. 4, pp. 585–597, 2002.

[17] J. Bień, M. Kużawa, M. Gładysz–Bień, T. Kamiński, "Quality control of road bridges in Poland", Proceedings of the 8th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2016, Foz do Iguaçu, Brasil, pp. 971–978, 2016.

[18] J. Bień, M. Kużawa, T. Kamiński, "Validation of numerical models of concrete box bridges based on load test results", Archives of Civil and Mechanical Engineering, vol. 15, no. 4, pp. 1046–1060, 2015.

[19] N.M.M. Maia, J.M.M. Silva, E.A.M. Almas, R.P.C. Sampaio, "Damage Detection in Structures: From Mode Shape to Frequency Response Function Methods", Mechanical Systems and Signal Processing, vol. 3, no. 17, 2003.

[20] M. Kużawa, T. Kamiński, J. Bień, "Fatigue assessment procedure for old riveted road bridges", Archives of Civil and Mechanical Engineering, vol. 18, no. 4, pp. 1259–1274, 2018.

[21] M.L. Wang, J.P. Lynch, H. Sohn, Sensor Technologies for Civil Infrastructures, Volume 1: Sensing Hardware and Data Collection Methods for Performance Assessment, Elsevier, 2014.

[22] Ch.J. Wall, R.E. Christenson, A.–M. H. McDonnell, A.A. Jamalipour, Non–Intrusive Bridge Weigh–in–Motion System for a Single Span Steel Girder Bridge Using Only Strain Measurements, Connecticut Department of Transportation, Report No. CT–2251–3–09, 2009.

[23] PN-89/S-10050. Bridges – Steel structures – Requirements and testing.

[24] PN-S-10040:1999. Bridges – Concrete, reinforced concrete and prestressed concrete structures – Requirements and testing.

[25] E.O. L. Lantsoght (Editor), Load Testing of Bridges. Series: Structures and Infrastructure, Taylor and Francis Group, Vol 12 & 13, 700 p., 2019.