# Monitoring of Bridges with Static Strain and Displacement Data

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## ABSTRACT

Monitoring of the static response of bridges under service and environmental loading has been recently considered a valid alternative to the more classical methods based on the measurements of the dynamic response and subsequent dynamic system identification. The paper starts reviewing and comparing some of the most common data processing techniques used both in dynamic and in the static monitoring fields, with the aim of outlining the main differences in the characteristics of the information extracted. A discussion is also presented, based on experiences gathered both from practical applications and from research experiments, on advantages and disadvantages of the static monitoring approaches. The reliability of the damage assessment process via static monitoring techniques will also be addressed.

## INTRODUCTION

The assessment of the actual safety conditions in bridges and similar structures, like harbor piers or other structural systems characterized by a one-dimensional development of the main structural component and subjected to bending and shear, is a very important issue in infrastructure management, as shown by so many papers presented in recent relevant Conference Series. An interesting review of the current methods for performance evaluation of existing bridges, including field measurements, has been presented by Kim et al. [1].

To the purpose of assessing the actual structural conditions of bridges, in the recent 15 to 20 years a significant research and application effort has been devoted to the development of instrumental Structural Health Monitoring (SHM) techniques.

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Innovative sensing technologies like fiber optics and various types of contact and non-contact sensing have been introduced to monitor a large variety of quantities among which strains, displacements and vibration. Different data interpretation techniques aimed at detecting the presence of damage or degradation due to ageing, overstressing or accidental events have also been proposed in the literature and applied in the field. As concerning the physical quantities that are measured by the monitoring system to characterize the structural response, a further distinction can be made between static and dynamic quantities (displacements or strains, accelerations).

When dynamic measurements are of concern, at every measurement campaign high frequency data streams from the different sensors are repeatedly collected in batches of several minutes while, in the static case, only single data values are collected from the sensors.

If an instrumentation system is permanently installed on the structure allowing both static and dynamic measurements, the different approaches can be easily combined. Mixed-mode SHM approaches are indeed very useful in practice because they may lead to combine the best features of the different methods and of the corresponding data interpretation techniques.

Assessment methods based on the interpretation of dynamic measurements have been used since a relatively long time and a very extensive literature is available on the subject [2]. Standards and recommendations for performing dynamic measurements on bridges and viaducts are available as well (ISO 14963:2003, ISO 18649:2004).

Static displacement and deformation measurements have always been the most common tool in proof-loading of bridges, but their use as a SHM tool based on continuous recording of the static response is more recent. It is however believed that permanent static monitoring can be at least as valuable as dynamic monitoring.

In view of a more extensive use of the static monitoring approach, in combination and not necessarily as an alternative to dynamic monitoring, the present paper is aimed at discussing some of the characteristic features of both methods and at presenting in a greater detail strength and weaknesses of the static monitoring approach.

## DYNAMIC MONITORING APPROACHES

According to the classical approach in dynamic monitoring using ambient vibrations, the condition evaluation (or damage identification) is fundamentally based on the process described by the flow-chart of Figure 1a.

The system identification step is usually performed by means of a variety of standard algorithms; one of the most used is for example described by Brincker et al. [3]. The system identification process can be deployed on the basis of accelerometric measurements but strain time-histories can also be efficiently used.

Detection and interpretation of anomalies in the sequence of dynamic properties that are generated by the repeated vibration measurements and system identification steps is a complicated process that often requires comparison with the results of finite element dynamic models and correlation analyses with environmental data. Indeed, changes in eigenfrequencies, modal shapes and dissipation properties may also be caused by factors different from damage or structural degradation.

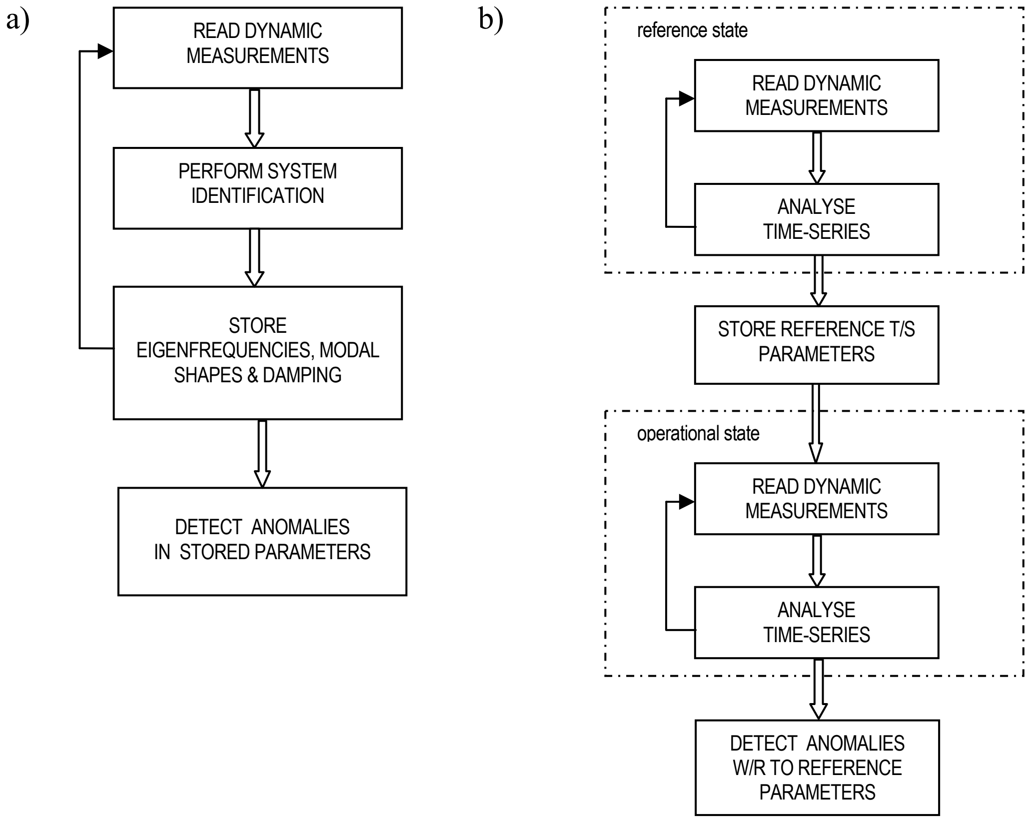


*Figure 1. a) The conventional dynamic SHM approach; b) Time-series based dynamic SHM approach.*

Temperature, humidity and support conditions as well as the presence of vehicles on the bridge may cause variations in the dynamic properties of the same order of magnitude of the ones caused by structural damage, thus introducing significant uncertainties in the process. Different methods for correcting those influences and filtering out undesired effects have been presented in the literature and experienced in the field [2]. In order to properly apply these correction methods, measurements of the relevant physical parameters and eventually traffic conditions are of course needed.

The same processes can be utilized when forced vibration measurements are periodically repeated.

All the above approaches either explicitly or implicitly refer to a behavioral (finite element) model of the bridge that may actually be updated at the end of each measurement cycle to reflect the real structural conditions and that can be used to interpret the future structural responses and to assess the residual life of the structure. For this reason, these methods can be considered as model-based approaches.

As an alternative, or complementary to model-based approaches, non-model based approaches can also be applied. These methods mainly consist in the processing of the time histories of the response to extract some characteristics of the signals, the variation of which may later be referenced to the presence of structural damage [4]. Feature extraction may be performed by means of a variety of algorithms such as ARMA models, Neural Networks, Wavelets or other signal processing tools [5].

When time series based damage detection algorithms are applied, such algorithms also require a sufficient number of reference signals, i.e. measurements referable to undamaged states, in order to render effective the usage of pattern recognition schemes.

Time series based methods are typically output-only but correlation with time series of the environmental parameters or traffic intensity records (weight-in-motion) may be needed to interpret variations in the parameters. The process corresponding to the time series based dynamic approach is quite different from the classical one and is represented by the flow-chart of Figure 1 b.

When considering the time series based method, it has also to be noted that the determination of the parameters in the reference state may require a long observation time, depending on the statistical model used to characterize the series and on the phenomena influencing the signal noise. This observation time is not needed in principle when using the conventional approach but anomalies in the dynamic parameters of the structure can be reliably detected looking at records extended over long periods of time (e.g. through the use of appropriate charts).

Nonetheless, accounting for environmental effects may require repetition of dynamic measurements and identification of dynamic structural parameters over periods of time of sufficient length compared to the environmental phenomena under consideration. Structural conditions should remain constant during such periods.

## STATIC MONITORING APPROACHES

As already noticed in the Introduction, static load tests conducted on a bridge structure statically loaded with trucks representing the design or intended service loading is a very traditional way of assessing the structural safety of a bridge and still is one of the most used approaches in performance evaluation of bridges [1].

Long-term static monitoring of structural systems, performed with a permanently installed instrumentation system, has been developed quite recently. Among the first large-scale reported applications we recall the ones presented in [6-8].

Permanent static monitoring systems usually produce a tremendous amount of data, so that data fusion and data mining represent a very important step in the application of damage detection processes. Data processing and interpretation for damage detection can be performed according to the following methods:

- model based, input-output;
- non model based, output only.

### Model based static approaches

According to this approach, strains and deflections recorded by the instrumentation systems are compared with the values obtained by computer simulations on finite element models.

For a bridge, there are two main loading conditions that can be used to this purpose: temperatures and traffic loading. Temperatures may be recorded easily at the same time instants in which the response of the structure is detected. It is important to note that environmental temperatures are different from temperatures at the structural surfaces as these latters depend on solar radiation and exposure of the surfaces themselves. Temperature effects are usually the most significant state of deformation that is recorded by permanent static monitoring systems installed on a bridge [9].

Reproduction of measured temperature effects by means of finite element models allows a very accurate determination of the actual static conditions of the bridge, including structural stiffness characteristics and restraint conditions given by supports. Models tuned on temperature effects are very useful and reasonably accurate for the interpretation of the effects of traffic loading [9].

Traffic data can be recorded by weight in motions sensors; however, traffic data and strains or displacements are not generally recorded at the same time. In addition, weight in motion sensors give the shock effect of the wheels onto the sensor, which is a function of the weight and of the speed of the vehicle. By the other hand, measurements of the structural response are also influenced by the dynamic behavior of the bridge. Direct correlation between load data and the static (still) response of the bridge can only be performed occasionally for very slow vehicles. When available, video recordings of the traffic can be very useful in interpreting the measurements. Recent developments of image processing techniques can provide very valuable information on the type and characteristics of the vehicles. In general, correlation between the load data and the parameters of the structural response can be made by constructing and correlating the respective statistical distributions [10].

By means of this approach, the presence of damage may be inferred through the detection of anomalies in the structural response. In particular, stiffness degradation resulting from the comparison of measured data with model results can be referred to the potential presence of damage. Again, the damage identification process is based on the analysis of the evolution of tuned model parameters with time. Figure 2 illustrates the flow chart of a typical process consistent with the above mentioned approaches.

**Non model based static approaches**

Non model based approaches represent the most innovative aspect in the static health monitoring of structures. These approaches are typically output only in the sense that they don’t need expressly the knowledge of the loading conditions onto the bridge. However, the influence of environmental effects and namely of temperature can be very important. Consequently, temperature records should always be made available when processing static permanent monitoring data.

The present approaches consist in applying signal processing techniques to the time series of the data provided by the monitoring system. Strain and/or displacement records can be indifferently used to this purpose.

It has to be noticed that when using static data, the time series collect measurements taken over very long periods of time (typically several years). This makes a significant difference with respect to the processing of dynamic measurements, where the time series collect measurements that are recorded for periods usually less than one hour. In such series extended over very long periods of time the presence of malfunctions in the instrumentation and data acquisition systems quite often occur, resulting in lack of data and frequent outliers.

As a consequence, a preprocessing of the raw data is always needed in order to fill the data gaps and filter out the outliers. Several statistical techniques are available to accomplish this task. Several signal processing tools have been proposed to analyze the pre-processed time series for disclosing anomalies in the signals that can be referred to the presence of potential damage in the structure.

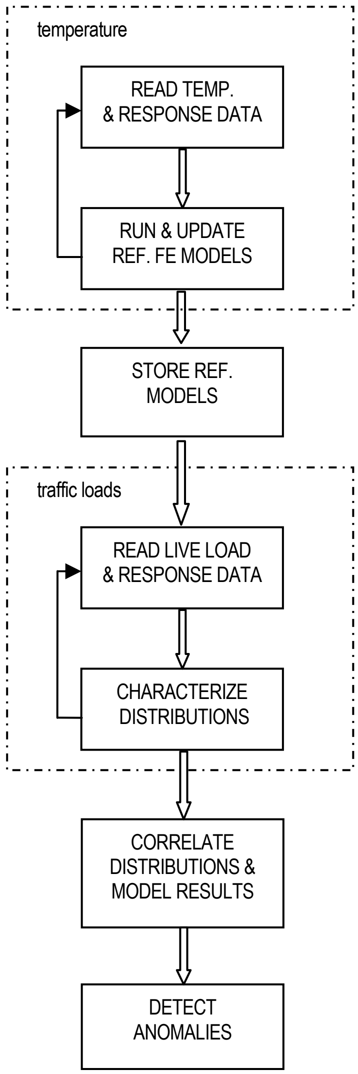


*Figure 2. Model based static SHM approach.*

In order to efficiently apply the signal processing algorithms for damage detection, time series of data extending over several years shall be available.

This marks a significant difference with respect to dynamic monitoring approaches because static approaches cannot, up to now, be completely validated by field applications. This means that the practice of using static monitoring systems for the condition evaluation of bridges is still at a relative infancy and more developments have to be expected in the future. Looking at the already developed and experienced methods, more information can be obtained from [11]. All algorithms require a long observation period to become stable and allow the detection of anomalies in the response. This period may range from two to four years, during which the structure conditions should be considered constant. In synthesis, the main algorithms that have been applied to the processing of static time-series are listed in the following.

*Predictive models*

A predictive model is a set of mathematical equations designed to forecast future behaviors based on current or historical data.

The advantage of predictive models is that they can be used to evaluate the measurements in real-time and set up warnings and alarms.

Predictive models can be updated during the lifetime of the system thus improving the accuracy of the forecasting. Several algorithms are available to construct predictive models, from ARMA and ARIMA models to Neural Networks.

*Correlation analysis*

This method is based on the consideration that a permanent change in the structural conditions will also produce a change in the correlation coefficients between couples of sensor time series and/or sensor versus temperature or live load time series. The process consist in calculating autocorrelation and cross-correlation coefficients for all the significant couples of time series and it can be applied and repeated at any time provided that the time series (or windows) considered are long enough to allow a reliable computation of correlation coefficients. If the structure behaves linearly, correlation coefficients are very close to unity. Significant deviations from unity indicate the potential presence of damage. In order to produce changes in the correlation coefficients, a relatively high number of measurements in the damaged state will be needed.

*Time series analysis*

Several algorithms applicable to the complete time series of data or on fixed or moving windows taken over the time series have been proposed and applied. Some of them work in the same way described for dynamic monitoring data. Others include the reference period within the time series analyzed and look for anomalies in the trends. Among the different methods, wavelets and wavelet packed decomposition, principal component analysis and proper orthogonal decomposition [12] have been proven to be effective for damage identification. The overall process closely follows the scheme of the flow chart of Figure 1 b and as a matter of fact time series based algorithms are more or less the same in dynamic and static monitoring approaches.

Time series based methods are however very sensitive to environmental disturbances in data such as anomalous temperature variations that produce noise in the signals. Better performances can be obtained when preprocessing of the data to reduce noise, e.g. by filtering out temperature effects, is applied.

## RELIABILITY OF DAMAGE IDENTIFICATION ALGORITHMS

In infrastructure management, several reliability-based maintenance strategies, able to keep a global measure of safety and effectiveness above acceptable limits, have been proposed in terms of lifetime functions and life-cycle-cost optimization [13]. Applications to bridges and to general structures form the subject of series of conferences organized by international associations like IABMAS and IALCCE.

Lifetime functions are recognized as a very useful tool in the construction of decision support systems for the management of maintenance operations of constructed facilities. However, the determination of lifetime functions and their updating from monitoring data is affected by both epistemic and stochastic uncertainties. Lifetime functions can be constructed at the beginning of the operational life of a bridge from theoretical/experimental or even heuristic degradation models and, if a Structural Health Monitoring system is installed on the structure, at any required time, the actual state of degradation (damage) can also be determined by applying a damage identification process allowing updating of the lifetime functions.

In order to avoid propagation of uncertainties in the decisional process, the issue of the reliability of damage identification algorithms plays therefore a paramount role in structural health monitoring techniques and in the related decision support systems for facility management approaches.

Several studies have been published in the literature to deal with uncertainties in the structural damage identification process, among which [14-15]. In the referenced studies non classical representations of the uncertainties, like fuzzy numbers and Dempster-Shafer theory of evidence, are presented. Zonta et al. [16] have instead presented a classical Bayesian approach to evaluate the impact of monitoring on the decision process in bridge management. A Bayesian approach based on previous works by Schoefs et al. [17] has also been developed to evaluate the level of confidence in damage identification [18]. This latter approach is based on the calculation of Receiver Operating Characteristic curves, originally established for the evaluation of the efficiency of non-destructive testing and has been proved to be effective also for the evaluation of the reliability of damage identification algorithms.

The issue is however not simple and the different approaches shall be mainly validated by field experience.

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