Disponible en **www.hormigonyacero.com**
0439-5689 / Hormigón y Acero 2021; 72(294/295):195-203
https://doi.org/10.33586/hya.2021.3033

Permanent Structural Health Check of Signature Bridges

Comprobación permanente del comportamiento estructural de puentes singulares

Helmut Wenzel[a]

[a] *WENZEL Consult, Vienna, Austria*

Recibido el 13 de octubre de 2020; aceptado el 18 de febrero de 2021

ABSTRACT

Asset management of signature bridges requires innovative approaches. Decision making cannot follow available codes and standards because these do not cover the extraordinary size and importance of these assets. Decision making in asset management shall be based on reliable data and prediction technologies.

In order to ensure safety, durability and operability, information on the structural performance of the respective bridge is required. Monitoring producing information on the performance of these structures has become mature after intensive research and development funded by the European Commission. Most of the parameters that describe bridge performance can now reasonably be monitored.

The paper includes an example of successful implementation, refers to a useful classification and specifies the applicable standards that can provide a framework for risk-based asset management approaches.

KEYWORDS: Bridge performance, structural health management, monitoring of signature bridges, decision making, asset management, risk based application.

RESUMEN

La gestión de puentes singulares requiere enfoques innovadores. Las decisiones no pueden basarse en los códigos y normas disponibles porque estos no cubren el gran tamaño y la importancia de estas infraestructuras. La toma de decisiones en la gestión de estas infraestructuras se basará en tecnologías fiables de gestión de datos y predicciones.

Con el fin de garantizar la seguridad, durabilidad y operatividad, se requiere información sobre el comportamiento estructural de cada puente. Los resultados provenientes de la instrumentación acerca del comportamiento de estas estructuras han llegado a un nivel de madurez después de una intensa investigación y desarrollo financiado por la Comisión Europea. La mayoría de los parámetros que describen el comportamiento del puente se pueden ahora supervisar razonablemente.

El documento incluye un ejemplo de implantación exitosa, presenta una clasificación útil y especifica las normas aplicables que pueden proporcionar un marco para el enfoque de gestión de infraestructuras basados en el riesgo.

PALABRAS CLAVE: Comportamiento de puentes, gestión del comportamiento estructural, Instrumentación de puentes singulares, toma de decisiones, gestión de infraestructuras, aplicación basada en riesgos.

1. INTRODUCTION

Performance-based bridge management is key when large infrastructure assets are part of the portfolio. It is common practice that such critical structures are equipped with monitoring systems that deliver the necessary data for performance assessment. As there exists a major gap between the high-tech monitoring technology and the cost-oriented asset management, it becomes necessary to introduce systems that satisfy both ends. A technology to perform permanent structural health monitoring with an easily understandable interface to operators is presented in this paper.

* Persona de contacto / *Corresponding author*:
Correo-e / *email*: helmut.wenzel@wenzel-consult.com (Helmut Wenzel).

Cómo citar este artículo: Wenzel, H., (2021) Permanent Structural Health Check of Signature Bridges, *Hormigón y Acero*, 72(294-295), 195-203, https://doi.org/10.33586/hya.2021.3033

Figure 1. Osmangazi Bridge, Turkey, 2016; 1550 m main span.

Signature bridges (figure 1) are designed and operated beyond the valid codes and standards. In order to ensure safety, durability and operability, information on the structural performance of the bridge is required.

Monitoring producing information on the performance of structures has become mature after intensive research and development. Most of the parameters that describe bridge performance can be monitored.

The question is: How can these data be converted into relevant information for decision making?

2. CLASSIFICATION OF BRIDGES AND RELEVANT STANDARDS

Bridges are prototypes. Any "one-size-fits-all" strategy will produce a large range of results. This does not support decision making but rather disqualifies any statistical approach.

The usual bridge inventories do not distinguish between a small single-span bridge and a huge signature structure. To get useful results on fleet level, it is proposed to split the inventories into three categories as described below.

Depending on the character of the structure and its specific requirement, it is proposed to create three categories of bridges, which will receive different management approaches.

- Standard bridges represent 95 % or more of the bridge stock and can be handled by the existing technologies with standardised thresholds and risk scenarios.
- Special bridges: These cover bridges which require special attention due to either design characteristics, large spans or special exposure to environment. For these bridges more information is required, and monitoring systems are recommended. The target is a reduction of uncertainties. The structures will be handled on an individual basis with extended refined procedures.
- Specific Signature bridges (Landmarks): There are structures that desire the highest attention because of their specific exposure, known deficiencies or the magnitude of consequences in case of failures. Lack of resilience (i.e. Morandi Bridge collapse) and brittle behavior (i.e. Reichsbrücke Vienna collapse) are their character. These bridges shall be handled applying risk-based approaches covering also "Unknown Unknowns" under the advice of experts.

This paper addresses the last category of bridges.

Signature bridges are designed beyond existing codes and standards. Due to their extent and complexity, they do not fit into the applied standard frameworks. In order to clarify that these kinds of "extraordinary structures" are not covered by our Eurocode EN 1990, it is specified in the introduction that "extraordinary structures" require "expert engineering input" in order to assess the applicability of the code and to define necessary deviations. The usual way to understand signature bridges is monitoring of performance parameters and implementation of performance models.

Applicable Standards

The framework for application of the developed methodology are the following standards:

- ISO 55000 Asset Management [1].
- ISO 31000 Risk Management Framework [2].
- EN 16991:2018 Risk-based Inspection [3].
- ISO 21928-2 Sustainability Assessment of Civil Engineering Works [4].
- Further relevant standards to be case specifically selected.

Bridge Parts of the Eurocodes: A bridge designer should use EN 1990 for the basis of design [5], together with EN 1991 for actions [6], EN 1992 to EN 1995 [7]-[10] (depending on the material) for the structural design and detailing, EN 1997 for geotechnical aspects [11] and EN 1998 for design against earthquakes [12].

3. ASSESSMENT OF SIGNATURE BRIDGES

There are good reasons why monitoring based approaches are rarely accepted. Monitoring-based assessment has suffered from the absence of clear objectives when monitoring systems are planned and realised. Actually, everything could be monitored but at which costs? Another aspect is the absence of sufficient know-how and personnel in the asset management teams. If we consider these practical aspects, we will be able to design and implement useful systems that will receive the necessary attention and acceptance.

We mainly distinguish between objectives that are of scientific nature like the verification of design, the comparison of theoretical to actual performance or the behaviour in extreme events. This requires extensive monitoring systems and specific expert input in order to utilize the potential of a large expensive monitoring system.

On the other hand, asset management of bridges requires information on selected parameters on a long-term basis. This will allow the necessary quantified assessment of current condition and, depending on the length of record, a reasonable prediction of future performance.

3.1. Asset Management-Driven Monitoring Concept

Asset management desires smooth operation which requires a reliable steady structural performance (figure 2). In case performance is degrading, the main interest is on the remaining time of safe performance. Under our current bridge realisation conditions, it might take 10 years to activate a replacement of a bridge in a difficult environment. Therefore, the monitoring concept has to produce long-term records in this procedure. It has to be assumed that the data are evaluated automatically giving a warning when certain thresholds are passed. The dynamic signature of a structure has been found best suitable for this purpose.

Comparison of RiskMan Approach to Current Practice (from top down to bottom up)

The 3 procedures described below concern the most applied current practice by end users, the status developed by scientists in European projects (Samco – IRIS – SafeLifeX) and the objectives of the RISKMAN proposal. The approaches of these applications can be characterized by:

- Condition-based bridge management [13, 14] is performed on national level driven by day-to-day demands. Europe is extremely fragmented in this sector.
- The science-driven approach [15] developed in European projects implements the difficult transformation from deterministic to probabilistic and the inclusion of life-cycle management. The Technology Readiness Level (TRL) of this approach is at least two levels below the required one and is therefore not yet ready for wide practical implementation.
- The RISKMAN approach [16] identifies all the gaps, brings useful developments of numerous projects performed together and offers support tools for practical implementation. The transformation from "must-have" (top down) to "good-to-have" (bottom up) will be enabled.

3.2. Condition-based Bridge Management

The core of bridge management is still a rating by visual inspections, based on standards (i.e. DIN1076 [17]) or national guidelines (i.e. FHWA in the United States). This is by far the dominant procedure which is rarely supported by monitoring

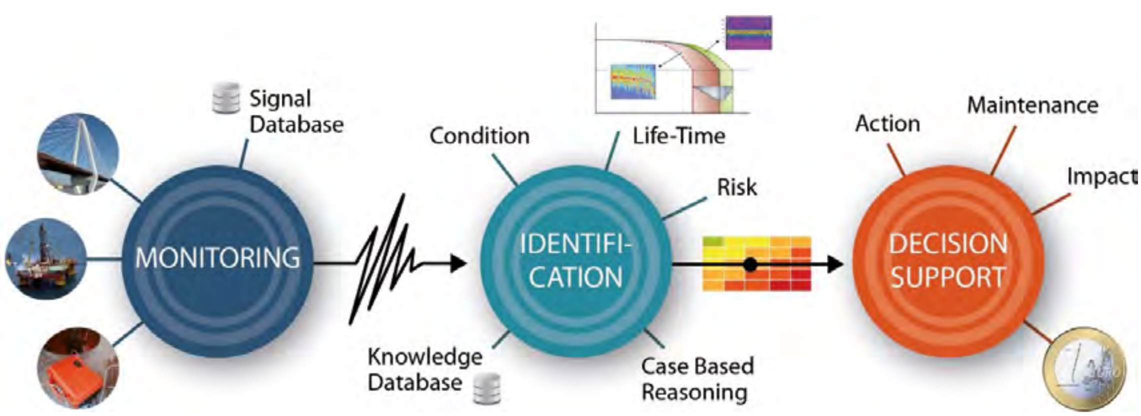

Figure 2. Flow diagram of the structural health management process (IRIS 2013)

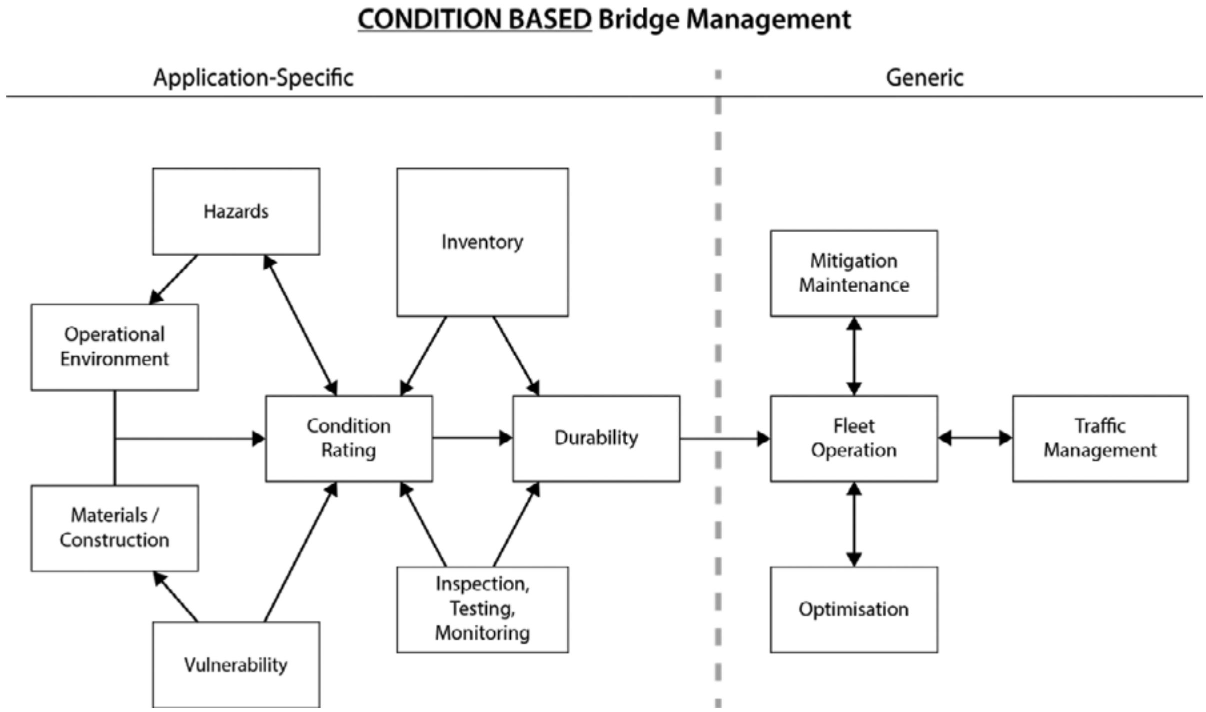

Figure 3. Current Practice in European Bridge Management

or testing campaigns. Materials and structural models are taken as given and are normally not re-assessed. This is sufficient to create a table of the fleet with a ranking of structures in terms of necessary investment in future (figure 3).

Deficit: A major setback in clients' organizations is the fact that future budgets are determined on the basis of the accumulated rating of the fleet. A low rating leads to more budget. There is no incentive for realistic assessment and proper management because it would end up with the penalty of lower budgets in future.

Deficit: A major hurdle in this procedure against the introduction of innovative development and applications is that the lack of applicable standards does not allow the replacement of the current procedure. This means that no money is saved in current procedures but additional costs for innovation are incurred.

3.3. *Proposed RISKMAN Bridge Management*

The following concept will bring a breakthrough in European Bridge Management procedures (figure 4). Closing the identified gaps will enable harmonised management applied to the proposed bridge classes. The latest challenges from sustainability goals (SDGs) to climate change are covered and all levels of infrastructure management can be satisfied

3.4. *Basic Concept of RISKMAN Bridge Management*

A typical risk management campaign starts after initial doubts on the performance of an industrial process, a structure or an element. Asset managers, and specifically the engineers working close to the process, have a very good idea where the weak points are. It is mainly based on experience and technical assessment. RiskMan supports the quantification of a suspect performance in order to support value-based decision making.

It is considered that decisions are made on various levels from the engineers and maintenance providers up to the top management of an enterprise. For this purpose, overarching perspectives have to be introduced.

Many parameters are involved in the performance of an asset. To make the process manageable and to present it properly, the spider diagram has been developed (figure 5). It groups the many parameters into 6 categories which become indicators by providing them with a quantitative value. The procedure is in the stage of becoming introduced to relevant standards and guidelines (i.e. ISO 21928-2 [4])

The 6 categories are:

- *Safety*: normally understood as ultimate limit state (ULS) by engineers representing the collapse of performance. (Note: This is not to be mixed with aspects of security which will be covered in the category society.)
- *Durability*: usually understood as durability limit state (DLS) by engineers, covers the change of performance over time until decisions on strengthening or decommissioning become necessary. The basis is a mathematical formulation of ageing representing the consumption of lifetime and the remaining lifetime allowing safe operation of the asset.
- *Operability*: operability limit state (OLS) describes the function of the asset to perform the objectives. This also covers maintenance, maintainability and necessary interventions. Typical performance models apply.
- *Economy*: any decision on asset management has economic consequences. These consequences might be process-related and cover many financial aspects. (Note: The

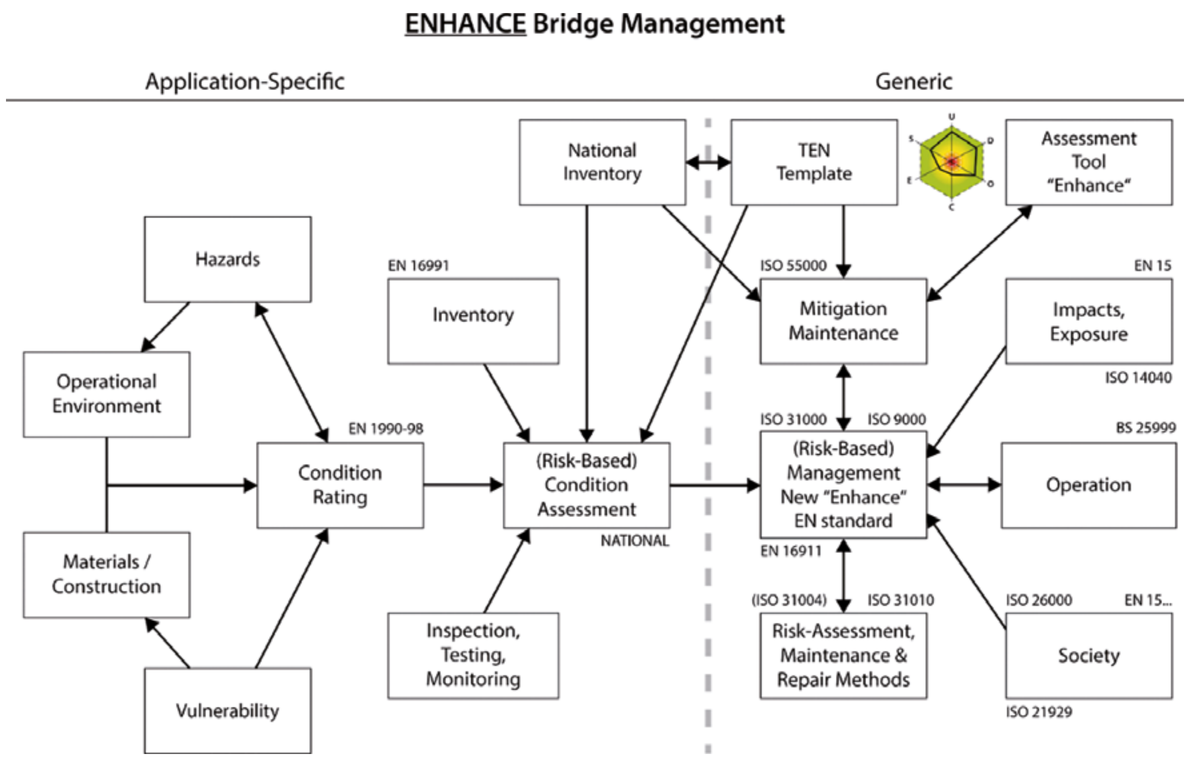

Figure 4. RISKMAN approach proposed (under publication by WCE in 2021); SHM indicators are produced in Inspection, Testing and Monitoring. Metrics for assessment are available in EN 16991 [3] and in diverse ISO Standards (i.e. ISO 21928-2 [4]). In EN 1990-98, TC250 and SCs are handling the subject for implementation in future revisions.

impact on local economy is covered by the category society). Double counting has to be avoided.

- *Environment*: the ISO standard 21929 [18] provides a framework on the relevant parameters in this sector. Details are provided in this publication and the tools contain computational routines for application. (Note: There are many parameters which might outbalance themselves by leading into different directions. The pros and contras have to be carefully separated.)
- *Society*: this covers the influence on society, specifically human well-being, opportunities and development from local to global scale.

In order to achieve a numerical result, values for each parameter combined to an indicator (for each category) has to be created. It is desirable to receive a rating for each scenario. The rating is based on models that represent the hazard side (excitation models) and the resistance is covered by structural or system models that describe the capacity of a structure or system (vulnerability). This is covered in figure 4 by the left side of the diagram and is case specific.

This procedure can be applied within each of the categories involving as many parameters as necessary. A final assessment can then be shown as an index which is an aggregation of the 6 individual indicators. This allows separation of different procedures as well as another weighting to express potential political or subjective importance (covered by the right side of figure 4; generic part).

This procedure supports the following three indices:

- *Mean Rating*: The simplest way is to provide a mean of the ratings of the 6 categories. This is applicable when ratings are better than 3.
- *Weighted Mean Rating*: It can be refined by adding weights on the categories of specific interest or subjective importance.
- *Relation to perfect Performance*: Actual Performance can be expressed as fraction of perfect performance by computing the area under the hexagon in the spider diagram in comparison with the total area (all ratings are 1). This is specifically helpful when comparison of alternatives is studied.

Decision making can be done based on the rating applying the rules established on fleet, national or global level. A useful framework for application can be taken from ISO 55000 (asset management framework [1]) and ISO 31000 (risk management framework [2]).

4.
DYNAMIC SIGNATURE AND PERFORMANCE

This chapter covers the largest and most important activity of the Structural Health Monitoring (SHM) operation.

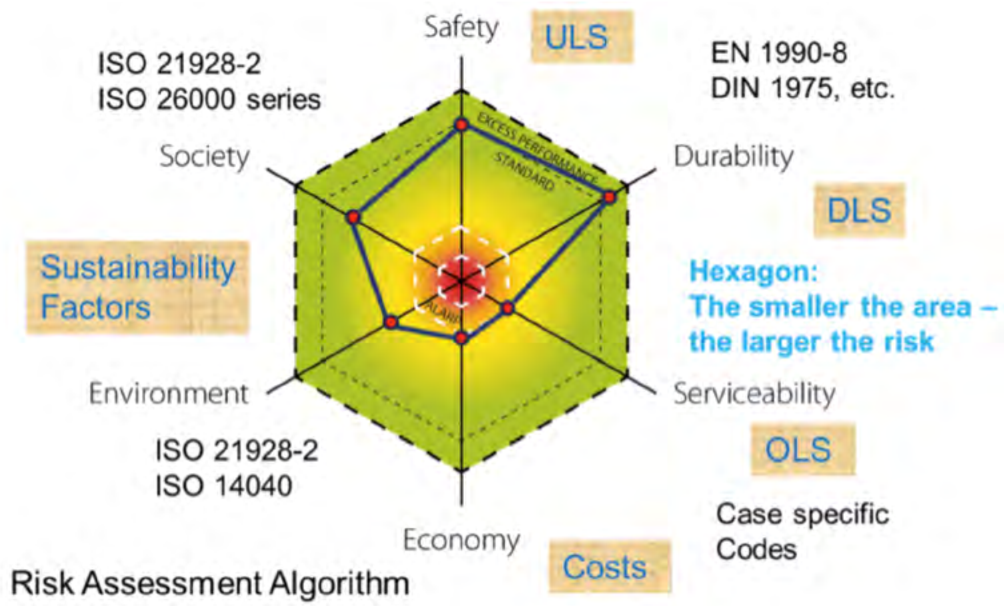

Figure 5. RISKMAN assessment algorithm. Example of an unidentified case. The rating for each of the 6 categories is determined by case specific parameters fed into respective models.

4.1. Background (Physics)

The performance of a structure depends on the physical properties. If they change, maybe through damage or ageing, the dynamic signature also changes.

The dynamic signature is mainly represented by the following changes:

- *Shift of frequencies*: Frequencies shift with a change of stiffness or changes in the boundary conditions.
- *Damping behaviour*: Damping factors mainly change with changing boundary conditions or possibly in post-strain.
- *Drop in amplitude*: The amplitude of a frequency depends on the energy input. A decreasing energy input indicates energy losses from the system or energy transfers to higher modes.
- *Energy transfer*: If energy is transferred to higher modes, this provides an indicator for ageing or inherent damages.

The best way to visualize these four phenomena is to show subsequent records in a trend card. It shall be considered that there are natural trends, for example changes in frequencies due to temperature changes, which have to be compensated before a direct comparison is made.

4.2. Window (figure 6)

In order to use the full potential of these methods, it is advisable to sample the most relevant accelerometer with a frequency of 500 Hz. This will cover the most interesting areas around 80 and 200 Hz respectively.

- Show the trend over a chosen time frame for frequencies between 0 and 5 Hz to give an overview on the fundamental frequencies.
- Provide a trend card for the same time slot covering the frequencies from 0 to 25 Hz which enables a look at the performance of higher frequencies representing local phenomena.
- Provide a trend card for the same time slot covering the frequencies from 0 to 250 Hz to show any energy transfers from fundamental to higher frequencies.

Trend cards show a view on the normalized spectra computed for every chosen file. The best representation is a 2D-display with colour coding. Low energy is seen in blue with rising amplitudes towards red. The subsequent figures shall show this in detail. The individual computational steps are described as follows:

Typical examples of trend cards are provided. A dynamic window is proposed that provides an automatic scale on the amplitudes to bring out the energy hot spots reasonably.

Note: A direct comparison of individually computed trend cards can only partly be made due to the dynamic window. In case that longer time slots shall be looked at, a new time frame is to be defined and recomputed.

The window shall show a clear indication on the time frame selected on the horizontal axis, and the frequencies that are covered by the image on the vertical axis.

4.3. Interpretation

The interpretation of the trend card is looking into the following phenomena:

- The fundamental frequencies normally form a horizontal line. Every deviation from horizontal represents a shift in frequency. Shifts in frequencies are normally rare and are mainly depending on temperature changes. In case that a shift of more than 5% is detected, expert advice shall be collected.
- The spectra should represent an equal distribution of energy. Energy is shown by different colours. Any energy

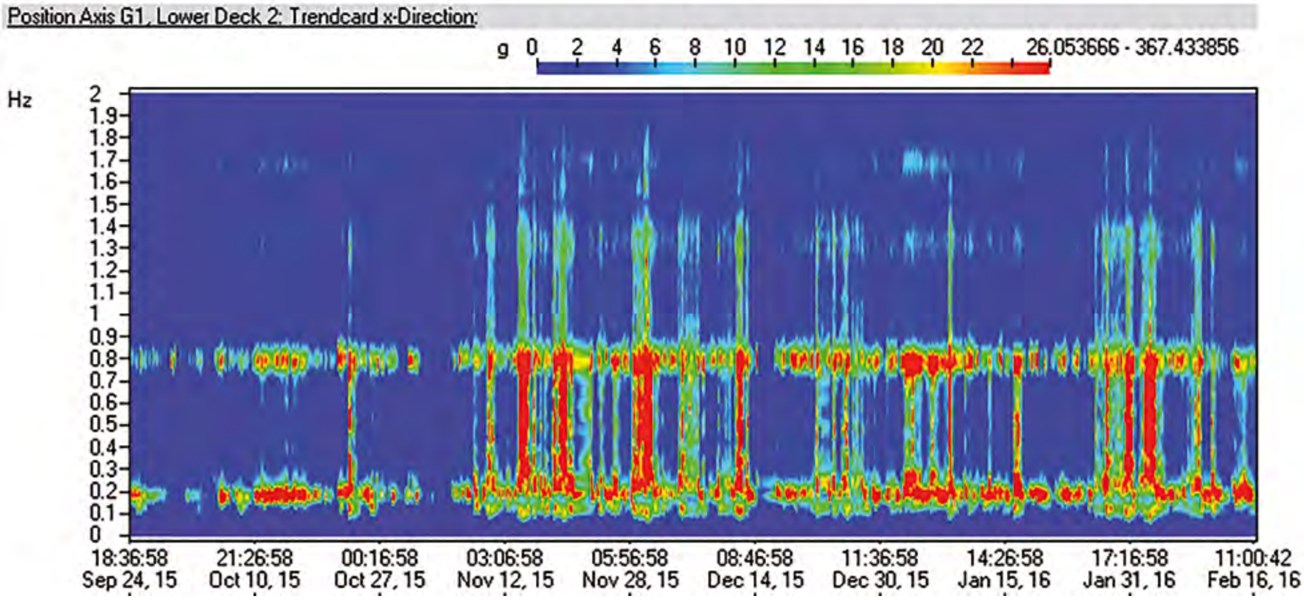

Figure 6. Typical trend card shows performance over time (frequency/time). This trend card shows the dynamic signature of a damaged structure. Energy transfer between the fundamental modes becomes visible when the excitation level is high. This is not a desired performance of the structure and leads to damage.

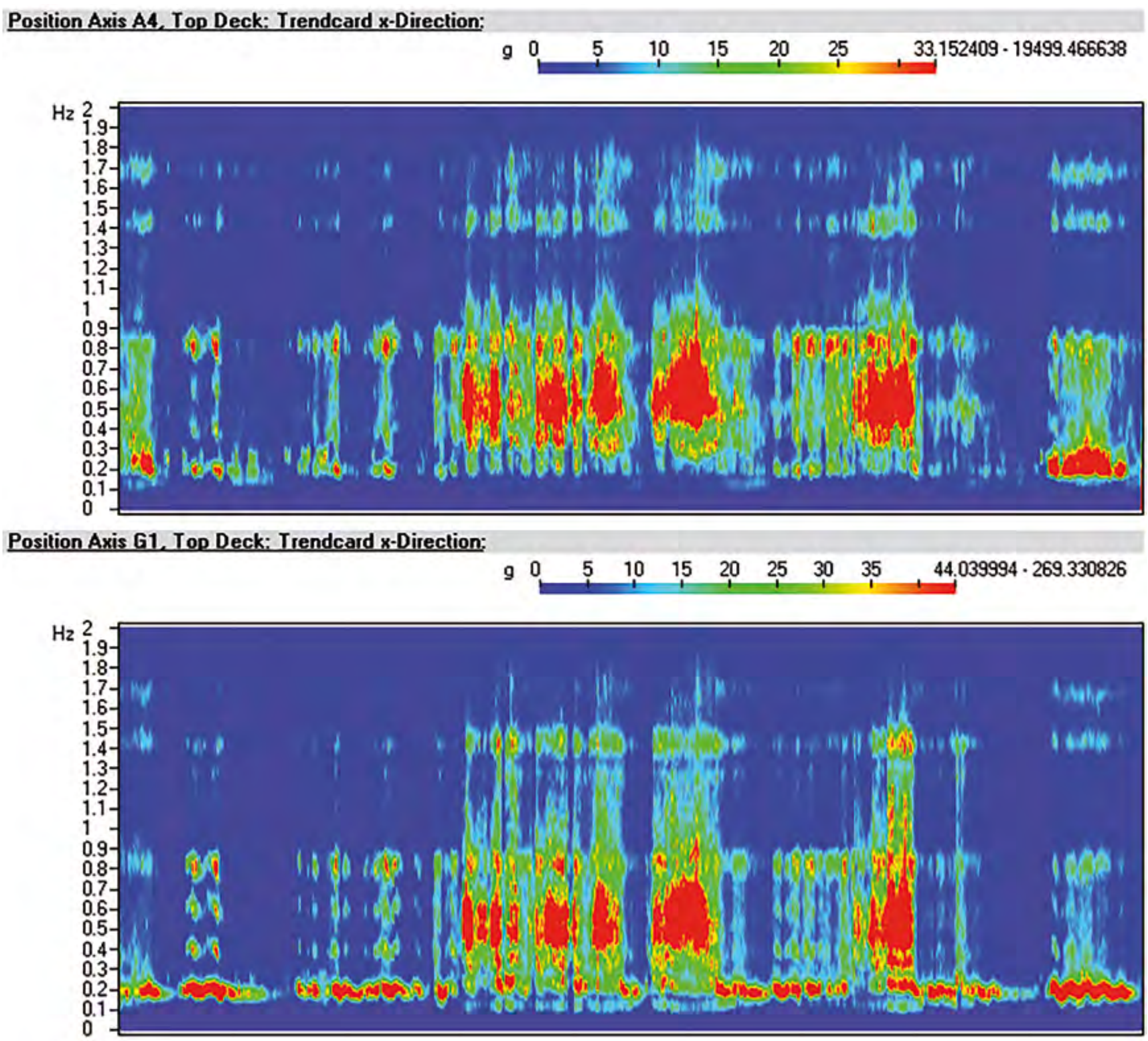

Figure 7. Typical trend card with change in performance after damage as used for reporting

drifts are easily identified by looking at the image. It is not advised to go for an automatic detection.
- Damping is represented by the width of the individual point in the trend card. If there are distinctive points, the spectra shall be analysed individually.

The trend cards shall be used in reporting and it is desired that the term "performance as expected, no specific irregularities" shall be used.

4.4. Algorithms

The following algorithms shall be applied:

It has been proven successful to start with simple routines, which show you when change happens. The most successful approach is a frequency analysis which produces results in form of Trend Cards. The routine is the following:
- Select a reliable channel with good and relevant data (subsequently always use the same channel for comparison).
- Select a suitable time window (usually we take one at the max and min temperature. This could be at 07:00 and 17:00h.
- If you sample with 100Hz make the window about 32000 (2over16) points long. This relates to a record of 5min 30sec. For fundamental frequency identification the record has to be 10 min long (First vertical mode below 0,10Hz).
- For this specific bridge a record of 10 minutes is preferable. To get them it is necessary to link 10 records to 1 file.
- Apply an FFT to create a spectrum and store it with a time stamp.
- Select a time window for the trend card (min for one month but better for longer periods).
- Create 6 trend cards. 3 for each temperature, one 0-5Hz, 0-50Hz and one 0-250Hz each. The first one shows the fundamental modes, the second one eventual higher mode and the last one energy transfers.
- The spectra used for each trend card should be normalized by equalizing the area below the curve. The area below the curve represents the energy content of a record. This will bring out eventual high energy events and show where to look at. (Details of normalisation see chapter 4).
- Modes should now be in a horizontal line and deviations become visible (refer to figure 7 below, this is an example where higher modes appear after damage).

4.5. Example

A typical example is presented below (figure 7)

This procedure will be relevant normally for the annual reports. Nevertheless, it would be useful to perform it earlier to get familiar with the process.

Finally, this should be performed by the software on demand giving a choice of frequency and time window.

Note 1: A continuous record without gaps is necessary to avoid misinterpretations.

Note 2: Trend cards can be produced monthly and then be connected to annual trends.

5. DISCUSSION

Operators have to be aware that the proposed methodology requires considerable simplification of an extra-complex performance model. This increases the probability that a possible important deviation might be overlooked in the first place. It will therefore be necessary to have a risk assessment routine available that assesses the risks and indicates those areas where a periodical closer look might be useful.

The selection of the relevant data for permanent monitoring plays a key role. The more data are displayed, the more information you get. Nevertheless, the more information you have, the more difficult the assessment will be. Therefore, the concentration on a limited number of parameters is strongly recommended and the routines that determine the relevant thresholds for warning and alarm shall undergo a permanent revisit and upgrade.

There has to be a balance between investment and value received from monitoring. The very large systems (i.e. Tsing Ma Bridge in Hong Kong with over 1000 sensors) produce almost not manageable amounts of data. A good way of addressing this problem is to store raw data of any event in a permanent accessible way. This will allow coming back on it when new knowledge has been received.

The proposed procedure has not been developed to detect black swan events, but in careful consideration of the "unknown unknowns" might satisfy the desired safety level. Unknown unknowns can be covered by increasing the value of uncertainties in the risk quantification. This will produce a wider range of expected events and might lead to higher costs of prevention measures. This is an economic optimization issue and familiar to asset managers.

6. CONCLUSIONS

Application of the proposed methodology to several signature bridges, particularly the Osmangazi Bridge in Turkey, where the key application to suspension bridges has been developed, has proven the applicability to bridge managers and operators. A careful revisit of records of previous structures where damages have been experienced showed that all of these would have been detected with such a system if designed and installed properly.

It has to be mentioned that a clear understanding of the structure is necessary to make the right decision which sensors would show any deviation from normal in the first place. It therefore has to be recommended to run such systems in the first year of operation by experts who have created the model. This would enable the necessary update and sharpening of the algorithms and routines.

Systems that permanently monitor performance are used in many sectors. Nevertheless, in case of mechanical engineering the properties monitored are known on a much better level. The many uncertainties we experience in our civil engineering structures make things much more complex and difficult to handle. The proposed methodology is the best under the state of the art and technology. With growing operation numbers and time, the experience will show its applicability and value of information.

7.
ACKNOWLEDGEMENT

The described work has been developed in a series of research and development projects funded by the European Commission since 1995. The most relevant ones were the SAMCO network (FP5 contract G1RT-CT-2001-05040), conducted between 2000 and 2007, where a comprehensive list of stakeholders, a wide number of reference projects and recommendations for applications were produced.

Luis Ortega Basagoiti has been an important member of the Samco community which collected methods and technologies to perform structural health monitoring (SHM) of bridges on behalf of the European Commission. He played a major role in the introduction of these technologies into practice. The technologies described here are based on these works performed 15 years ago.

A breakthrough was achieved by the IRIS project (FP7 contract CP-IP 213968-2) where from 2008 till 2012 an integrated European industrial risk reduction system has been developed [19]. The formulation of ageing of bridges has been introduced into a European Standard [3].

Safelife-X (FP7 Grant Agreement No. 608613) handled the safe life extension management of ageing infrastructures, networks and industrial plants. It organized and developed the Code EN 16991:2018 [3] which is the basis for risk-based asset management.

The detailed technology described in this paper has been finalised in the RiskMan Project funded by the Austrian Research Funding Agency FFG (2018 – 2019).

References

[1] International Organization for Standardization (2014) ISO 55000 Asset Management. Overview, principles, and terminology.

[2] International Organization for Standardization (2018) ISO 31000 Risk Management. Guidelines.

[3] CEN (2018) EN 16991. Risk-based inspection framework.

[4] International organization for Standardization. (under progress) ISO 21928-2 Sustainability in Buildings and Civil Engineering Works. Framework for Methods of Assessment of the Environmental, Social and Economic Performance of Construction Works as a Basis for Sustainability Assessment. Part 2: Civil Engineering Works.

[5] CEN (1990) EN1990 Basis for Structural Design.

[6] CEN (1991) EN1991 Actions on Structures.

[7] CEN (1992) EN1992 Design of Concrete Structures.

[8] CEN (1993) EN1993 Design of Steel Structures.

[9] CEN (1994) EN1994 Design of composite steel and concrete structures.

[10] CEN (1995) EN1995 Design of timber structures.

[11] CEN (1997) EN1997 Geotechnical Design.

[12] CEN (1998) EN 1998 Design of Structures for Earthquake Resistance.

[13] Pichler, D. and Wenzel, H. (2005) *Ambient Vibration Monitoring*. Chichester, West Sussex: John Wiley & Sons, Ltd, ISBN 0-470-02430-5.

[14] Wenzel, H. (2009) *Health Monitoring of Bridges*. Chichester, West Sussex: John Wiley & Sons, Ltd, ISBN 978-0-470-03173-5.

[15] Wenzel, H. et al. (2013) *Industrial Safety and Life Cycle Engineering*. Viena: GRASL Druck & Neue Medien GmbH, ISBN 978-3-200-03179-1.

[16] Wenzel, H., Risk and Performance based Assessment of Bridges, FFG Project: 869929/46842; 2020; RiskMan Development Book expected to be published in late 2021.

[17] DIN (1999) DIN 1076 Highway structures. Testing and inspection. Deutsches Institut fur Normung E.V.

[18] International Organization for Standardization (2011) ISO 21929 Sustainability in bulding construction.

[19] Wenzel, H., Veit-Egerer, and Widmann, M. (2013) Life Cycle Analysis Applied to the New Jersey Case Study. In *Industrial Safety and Life Cycle Engineering (IRIS)* (H. Wenzel ed.), VCE Vienna Consulting Engineers ZT GmbH, Vienna, Austria, pp. 443-464.