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From Structural Health Monitoring to Risk based Infrastructure Management

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Risk based decision making in infrastructure management has seen growing importance recently. Structural Health Monitoring can provide a sound basis for the hazard assessment but also for the determination of vulnerabilities. Only an integral approach will lead to useful results for our owners of our infrastructure. This implies that explicit consideration is given to the interaction between all relevant agents, i.e. technical systems, nature, humans, stakeholders and organizations in the assessment of the risk associated with the system considered. In the context of sustainable societal development an intergenerational aspect of risk and decision making must be considered.

Structural safety is a major issue for our built infrastructure. These are highly strained structures of great societal importance. The safety of the people and the operation crew has always to be guaranteed. Furthermore the structural integrity and hence the operability and availability of the infrastructure must be ensured.

Therefore actual condition information in combination with a sophisticated maintenance planning is of major importance. Such systems which integrate monitoring and assessment providing a strong tool for risk evaluation and decision support for cost efficient maintenance planning are a current research challenge.

The paper will provide information on decision support for risk and safety management based on SHM at strategic, normative and operational level. A holistic perspective on the approach and principles will be provided with examples from bridge management and building assessment.

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From Structural Health Monitoring to Risk based Infrastructure Management

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ABSTRACT: Risk based decision making in infrastructure management has seen growing importance recently. Structural Health Monitoring can provide a sound basis for the hazard assessment but also for the determination of vulnerabilities. Only an integral approach will lead to useful results for our owners of our infrastructure. This implies that explicit consideration is given to the interaction between all relevant agents, i.e. technical systems, nature, humans, stakeholders and organizations in the assessment of the risk associated with the system considered. In the context of sustainable societal development an intergenerational aspect of risk and decision making must be considered. The paper will provide information on decision support for risk and safety management based on SHM at strategic, normative and operational level. A holistic perspective on the approach and principles will be provided with examples from bridge management and building assessment.

1 INTRODUCTION

Risk based decision making in infrastructure management has seen growing importance recently. Structural Health Monitoring can provide a sound basis for the hazard assessment but also for the determination of vulnerabilities. Only an integral approach will lead to useful results for our owners of our infrastructure. This implies that explicit consideration is given to the interaction between all relevant agents, i.e. technical systems, nature, humans, stakeholders and organizations in the assessment of the risk associated with the system considered. In the context of sustainable societal development an intergenerational aspect of risk and decision making must be considered.

2 STRUCTURAL HEALTH MONITORING OF BRIDGES

Bridges are the flagships of our transportation infrastructure, on which society heavily depends on. Operation and maintenance have become more and more complex with the increased age of our bridge stock. Structural Health Monitoring, as part of lifecycle management procedures, experienced a growing importance recently. To maintain and improve the high quality and high level of service to the public it is essential to know the lifecycle performances of structures to ensure long service life and durability.

Structural Health Monitoring of bridges comprises many approaches and aspects to be covered. This paper therefore concentrates on the current practice and methodologies of dynamic monitoring. The theorem that the health of a structure is expressed in its dynamic characteristic is exploited.

Other sectors like mechanical engineering or aeronautics are operating in conditions where the properties of their structures are well known and are operating under controlled conditions. Civil engineering has to account for numerous non-linearities as well as dominating environmental factors that are able to hide useful information in the records. This leads to the situation that the results carry a portion of uncertainty we have to deal with as good as possible. It is most likely that one or the other approach will be overruled by future research work and the methodologies considerably improved. It therefore is of highest importance that the raw data of any monitoring campaign are stored properly in order to apply new algorithms in future, or to enable qualitative comparison between subsequent measurements.

It further has to be mentioned that bridge management approaches are dominated by political factors or incidents like bridge collapses. This might hinder the best possible exploitation of the methodologies. It further has to be recognized that currently a search for proper bridge management procedures is underway, which might lead to adaptation of the described approach.

The vision for Structural Health Monitoring of bridges is an integratied decision support system, web based and featuring a most user friendly surface. It contains the following elements:

- A display embedded in a GIS environment reporting the status of any structure in a network
- A database with web interface
- Permanent and mobile monitoring units
- Data handling, transfer and cleaning routines
- A knowledge and history base for statistical comparison
- A database on dynamic bridge simulation including automatic model update routines
- A case based reasoning system to compute the proposals for decision making
- Interfaces to existing bridge databases and relevant codes and standards

The key to success are high quality data combined with realistic identified models and deterioration laws quantitatively supported by monitoring. The output can either be a reliability index, a safety level, a graphic symbol or any other output value as desired by the bridge owners. Due to the complexity of the subject there will be limitations to this approach which can be narrowed in combination with engineering judgment. There is a long way ahead of us before the computerized SHM systems will be superior to the experience of a senior bridge engineer. It is doubtful that the human input can be replaced in civil engineering entirely and a fruitful combination is proposed. The proposed SHM is to be seen as a tool and support for the bridge engineer as well as an indicator to the bridge operators when critical situations are developing and a human expert aught to be called.

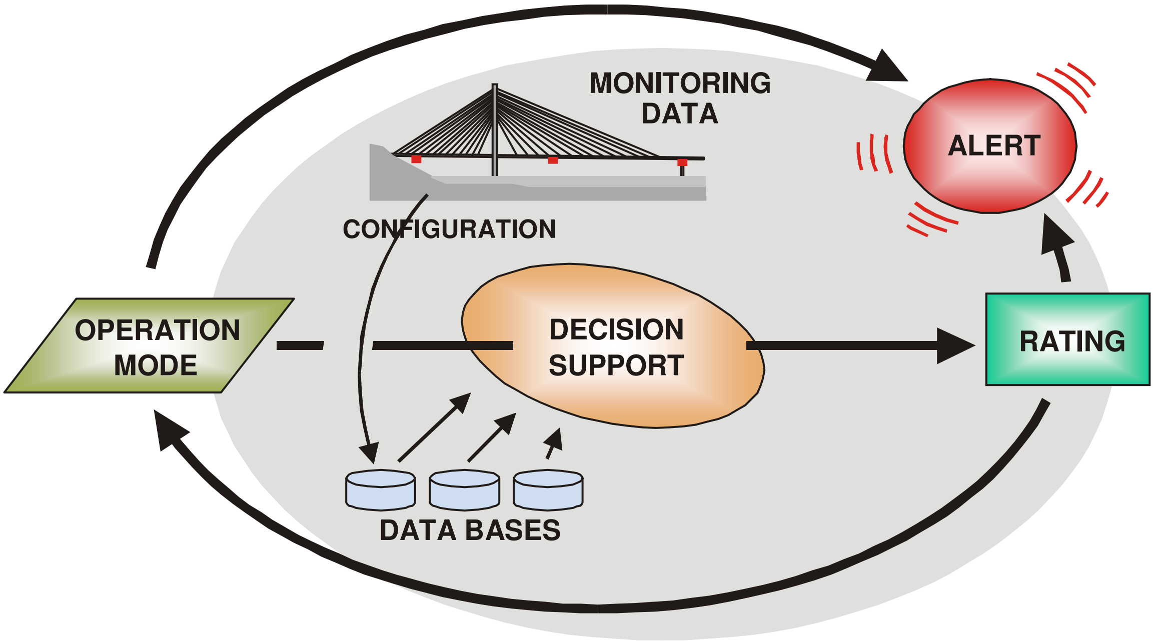


Fig. 1: Structural Health Monitoring of Bridges in practice

Structural Health Monitoring in practice requires a structured approach. Too often only fragments of the complete procedure are applied. The best and most satisfactory results will be achieved if all issues behind the following 12 activities are addressed.

1. SHM concept (clear objectives!) and design
2. Optimization and cost benefit analysis
3. Hardware
4. Software
5. Communication and web interface
6. Commissioning and start-up
7. Reporting structure
8. Periodic reporting
9. Analyses and expertise
10. Thresholds and warning levels
11. Periodic maintenance
12. System upgrade

Not all issues are necessarily addressed by the same specialist. Often teamwork is the way to succeed.

3 BRIMOS RISK LEVEL DETERMINATION

Within the BRIMOS classification procedure the BRIMOS rating provides a quantitative indication on the structural condition. The software computes risk values for the measured and computed dynamic parameters. Each parameter is computed separately and subsequently combined to an overall risk level.

3.1 Basic Concept

BRIMOS knows various levels of application depending on the depths of investigation. It is needless to say that this goes hand in hand with the costs involved. The following figure shows these levels with its elements. Any combination, depending on the case and the prevailing conditions will be applied in consultation with the owner of the structure.

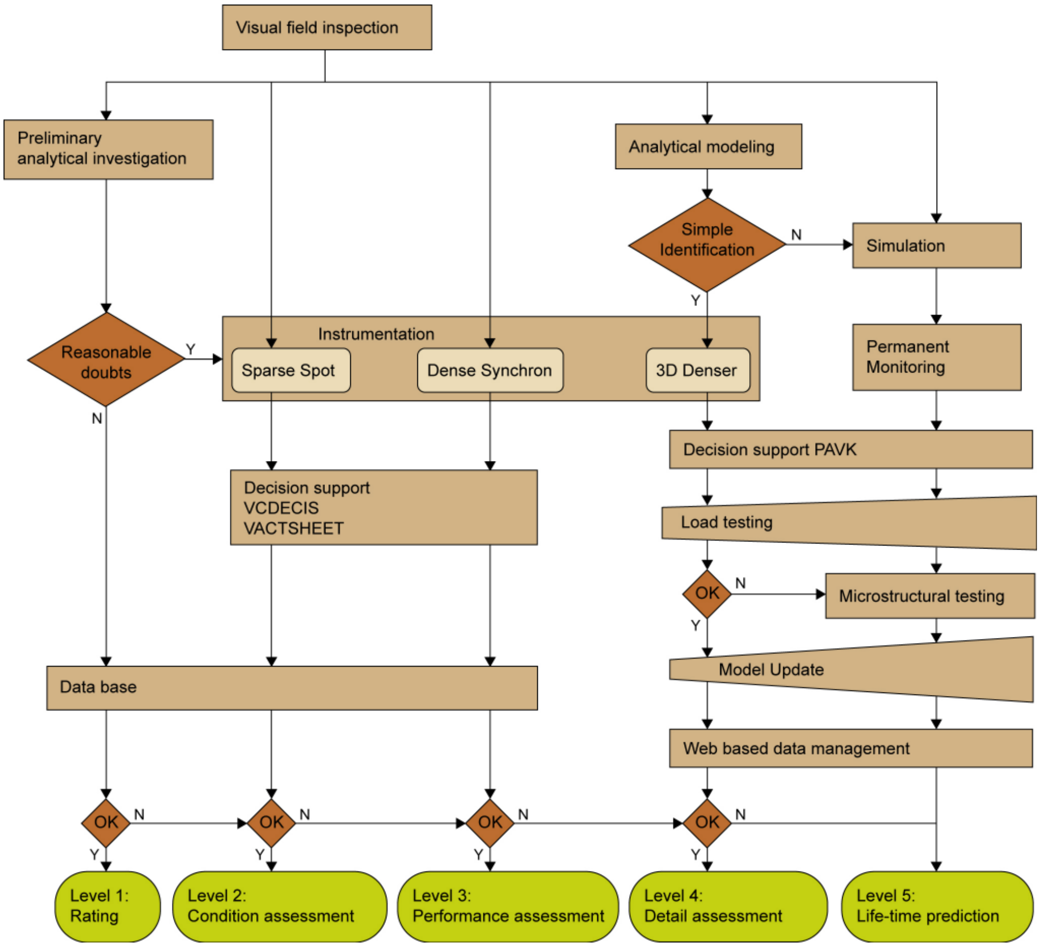


Figure 2: BRIMOS Classification Procedure

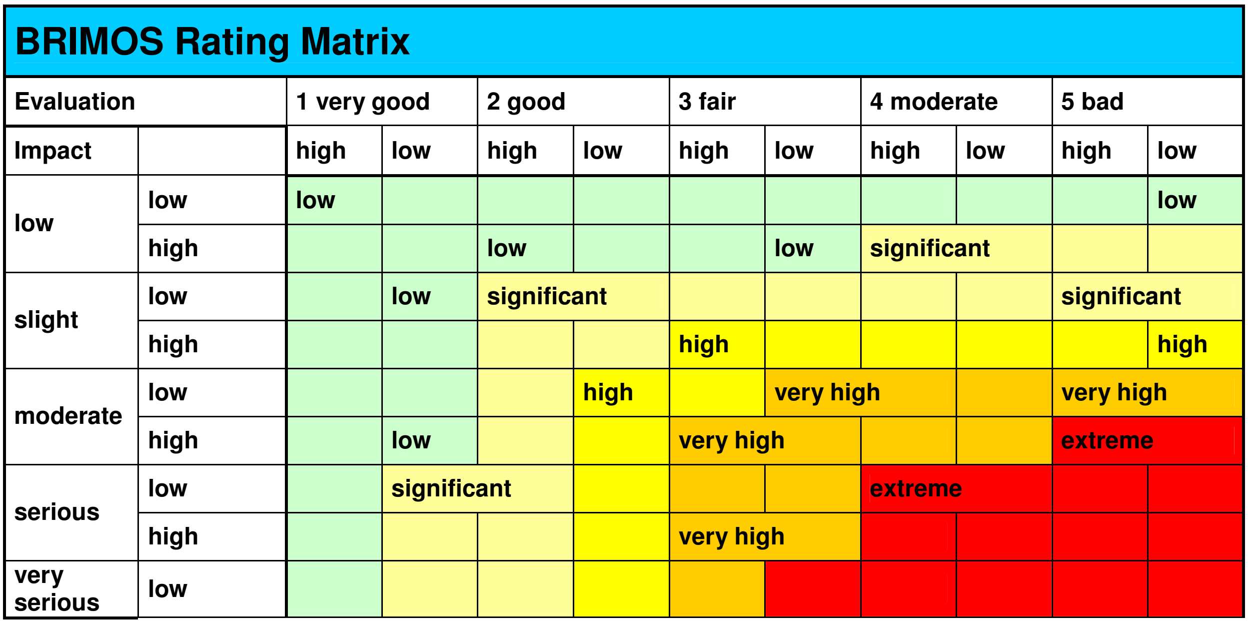
Rating

3 lines of rating are applied:

- Visual rating expresses the subjective impression of the inspection personnel. It can be the actual rating of the owner's inspection system or the subjective rating of the BRIMOS personnel.
- BRIMOS rating computes a value based on the measurements taken from the structure.
- FE model update provides the result of the comparison between the theoretical model and the results obtained from the measurements.

3.2 BRIMOS Rating

Risk is defined as the product of hazard and impact (consequences). A risk assessment matrix, as typically used in industrial risk assessment, is applied.



BRIMOS Rating Matrix

Evaluation		1 very good		2 good		3 fair		4 moderate		5 bad	
Impact		high	low	high	low	high	low	high	low	high	low
low	low	low									low
	high			low			low	significant			
slight	low		low	significant						significant	
	high					high					high
moderate	low				high		very high			very high	
	high		low			very high				extreme	
serious	low		significant					extreme			
	high					very high					
very serious	low										

Figure 3: Risk Assessment Matrix

The respective hazard is determined for each indicator separately and represents the computed value. For the consequences the decision support system provides a proposal based on knowledge from the database. A standard variance is set in the system which can be adjusted by the operator.

The BRIMOS damage detection concept foresees a combination of all indicators applied for the particular case. An internal check makes sure that false alarms are avoided by assuming that damage has to show in at least 2 of the indicators.

The involved attributes are:

- Eigenfrequencies representing the global stiffness of the structure
- Mode shapes indicating the dynamic behaviour of the structure
- Vibration intensities showing how much energy is absorbed by the structure as an indicator for lifetime consumption
- Local damping values as an indication were energy is consumed locally which indicates a potential failure mechanism
- Displacements as indicator on conformity with the theoretical calculation
- Dynamic factors as indicator on compliance with codes and standards

3.2.1 *BRIMOS Damage Indicator*

The dynamic characteristic of a structure is changed with the presence of damage. These changes follow patterns that can be detected from the signals. For this purpose it is important to compute system damping values. BRIMOS does this applying the Random Decrement Technique (RDT) using well defined trigger criteria. These values are compared to modal damping and the difference indicates the location and often the size of the damage.

Energy cascading is well known in dynamic systems with a change of conditions for a wave in the medium. These processes have been described by Kolmogorov and Richardson long time ago. It has been detected by VCE during extensive laboratory tests with real structures. The difficulty for application lies in the condition in the field, where environmental influences and particular unknown loading conditions cover this information within the records. BRIMOS has developed compensation routines which clean the records from environmental conditions and reduces the random loading pattern to an energy input consideration. For competition reasons the detailed combination laws and data mining procedures have to be kept secret. Nevertheless the principle and its background are reasonably explained in this document.

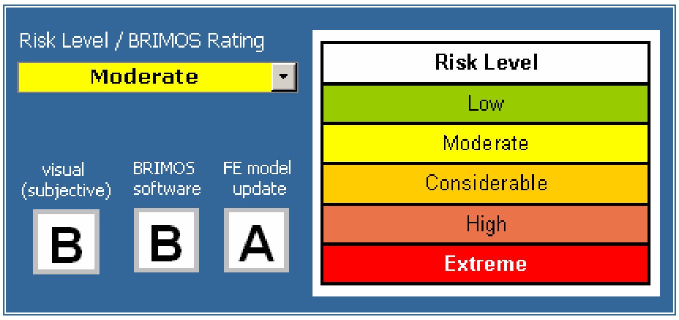
3.3 Involved Routines

The following development and resulting brands is used in this process.

- BRIMOS as the master and data handling system
- Vactsheet as a quick computation of dynamic parameters from the structure
- VCEDECIS, our decision support system handling the comparison of any new measurement with similar cases in the database and providing options from assessment
- VCDAMED as the particular BRIMOS damage indicator
- VCADE the methodology to assess the energy cascading process in the structure

3.4 Risk Level

All methodologies will be applied to any new measurement performed. The combination of the various ratings provides the risk level with accompanying standard deviation.



Risk Level / BRIMOS Rating: Moderate

visual (subjective): B
BRIMOS software: B
FE model update: A

Figure 4: Risk Level

The consequences from the measurement campaign are provided in the form of recommendations in short, medium and long term activities to be performed.

All results are stored in the BRIMOS database for the use and further improvement of the knowledge base.

4 DAMPING AS DAMAGE INDICATOR

Damping represents an issue that attracts controversies. This is due to the fact that there is no joint acknowledged ontology or well established definitions. This chapter reports on a phenomenon found during the numerous monitoring campaigns performed.

Damping calculated from a record depends on many factors, which makes it difficult to identify easily. In case that recording is done in a standardized way some of these uncertainties are eliminated. When we extract damping values, using the Random Decrement Techniques (RDT), we can find a pattern as demonstrated by figure xx. Records taken in distinct distances over the length of a bridge have a uniform damping value with the exception of the supports, where energy dissipation influences the result.

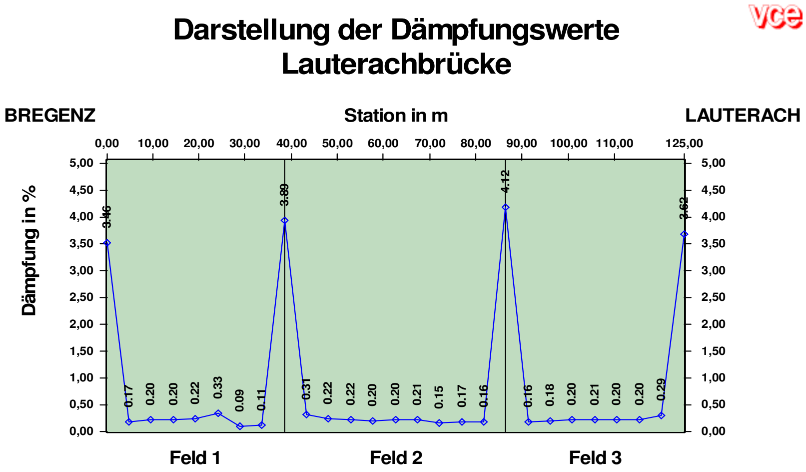


Figure 5: Damping values of a 3 span bridge

The figure shows the damping value extracted from a file which contains accelerations at a sampling rate of 100Hz and a length of 330 sec. The phenomenon is related to the non-linear behaviour of a bell with damage. Shadow frequencies develop when there is damage that affects the performance of the structure.

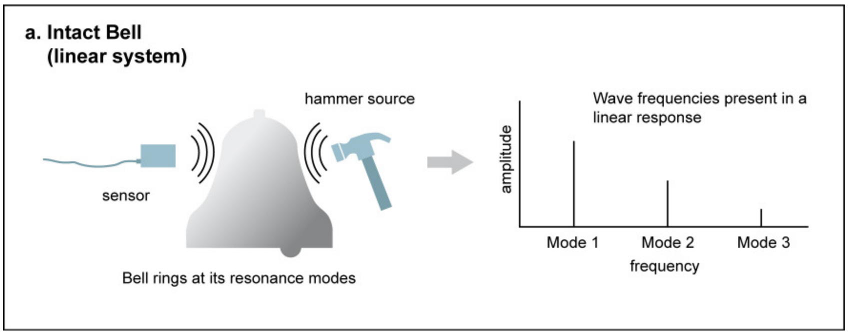


Figure 6: Spectrum of a sound bell

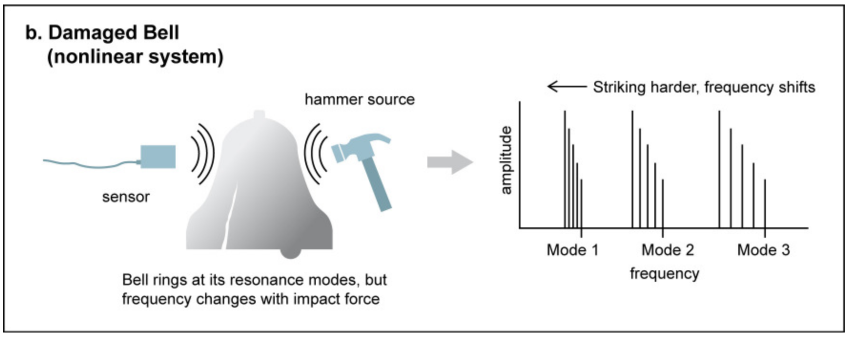


Figure 7: Spectrum of a damaged bell

The obvious effect of such behaviour is that the amplitude of the respective frequency is reduced when energy is leaking from the system. On the other hand the shape of the damping window is depending on the amplitude, because the isolated frequency is not clean, but rather contains elements of the overall structural behaviour.

There is consensus that damping is somehow amplitude dependent. Nevertheless the community has been convinced that this is eliminated by the RDT process. Under such circumstances the explanation for the deviating damping values for measurements at locations where damage is present, can only be related to the energy leakage phenomena.

This theory has been tried out at many occasions in laboratory tests and particular field tests. The experience was that particular in field tests at structures already in use for some time, have been reasonably successful.

Figure 8 shows the result of a single span bridge, which has been tested and treated by forensic engineering in order to find the damages. There is a very good correlation between the damping value and the damage.

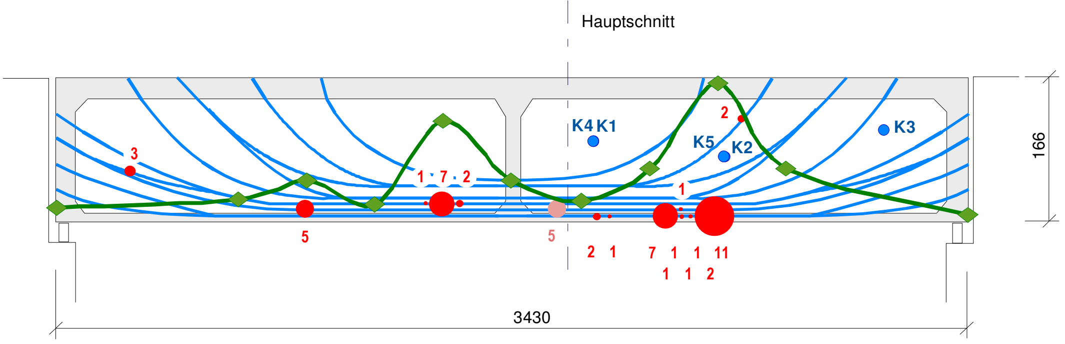


Figure 8: Damping values and damages found at the Regau Bridge

It shall be mentioned that this methodology is based on performance of the structure. Any damage, which is not relevant for the performance, will not be detected. This includes particular initial cracks of concrete structure (coming from creep and shrinkage), which do not consume energy during performance, will not be represented in the results. On the other hand broken post tension strand, where the load has to be transferred from one strand to another are expressed in the results.

A side observation made was that new structures or new laboratory beams hardly show these phenomena, even if intentionally damaged. The explanation is that this phenomenon can only be detected in case that the structure has already reached a state of well defined performance. This is not the case for new structures or laboratory specimen. The phenomenon is hidden by the fact that initial cracking has not been finished yet.

A statistics on the damages identified by this method also shows that the extent of the damage is represented in the damping value calculated. The values used in the current practice are related to this experience and can not be seen as absolute values. The dependency on measurement condition is not enough studied yet to compensate for eventual influences from environment and traffic. There is still considerable engineering judgment necessary to standardize this procedure and make it fit for general application. Nevertheless to use it as an indicator for potential damage it has been proven to be most valuable.

The average of the damping value calculated has been used for bridge rating as explained in another chapter. Its application particular to concrete structures has been proven to be the most valuable indicator for hidden damages.

A consistent mathematical proof of this theory is still lacking. This is mainly due to the many assumptions to be taken, which does not allow a closed solution. With the improvement of the elimination process of the other variables involved, this will be successful in the foreseeable future. As the methodology has been proven at many occasion successfully there is no objection against the application, always considering the limitation to performance relevant damage and the potential that the phenomena might be hidden by dominant other phenomena.

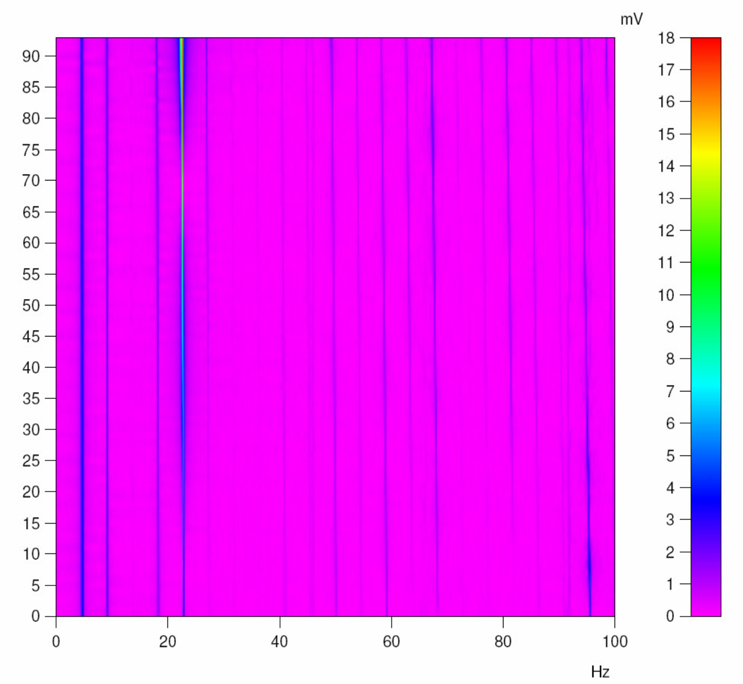


Figure 9: Spectrum of an undamaged structure

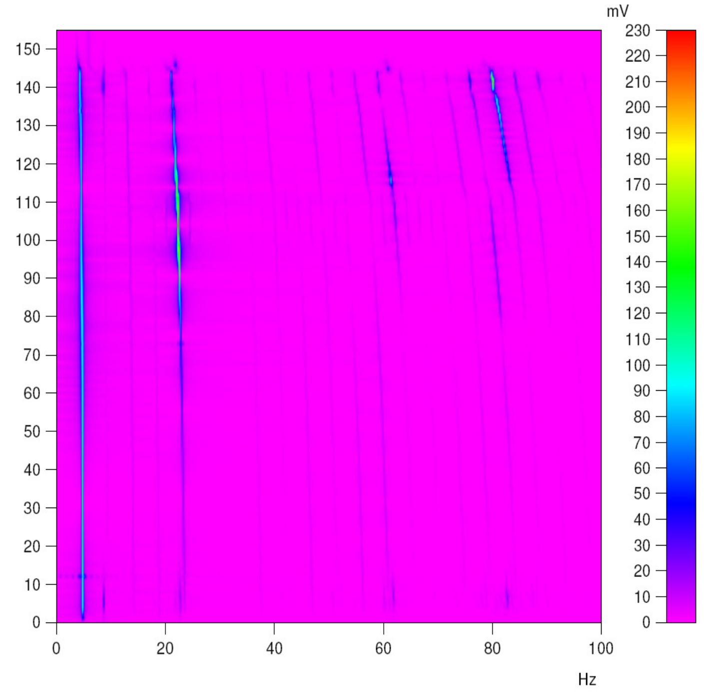


Figure 10: Spectrum of a progressively damaged structure

5 RISK BASED INFRASTRUCTURE MANAGEMENT

Structural safety is a major issue for bridges. These are highly strained structures of great societal importance. The safety of the people and the operation crew has always to be guaranteed. Furthermore the structural integrity and hence the operability and availability of the infrastructure must be ensured.

Therefore actual condition information in combination with a sophisticated maintenance planning is of major importance. Such systems which integrate monitoring and assessment providing a strong tool for risk evaluation and decision support for cost efficient maintenance planning are a current research challenge.

5.1 Lifecycle Cost

According to National Institute for Standards and Technology (NIST), "life-cycle cost analysis (LCCA) is a method for assessing the total cost of facility ownership." It takes into account all costs of acquiring, owning, and disposing of a building or building system. LCCA is especially useful when project alternatives that fulfil the same performance requirements, but differ with respect to initial costs and operating costs, have to be compared in order to select the one that maximizes net savings (www.wbdg.org)."

According to Christensen (2005), LCCA is more than a means to assess total cost of ownership or to distinguish between alternatives; it is the most relevant objective throughout the entire design and operation process. The often listed design goals of maximizing reliability, manufacturability (construct ability), durability, maintainability, etc., are clearly all desirable; however, when these objectives compete with one another there is no clearly-defined recourse. In contrast, basing designs on life-cycle cost removes the need for arbitrary rankings of attributes, and provides a basis for identifying trade-offs related to the bottom line. Christensen (2005) attributes this approach to procurement guidelines of both US and Canadian armed forces and notes that in 1960, US Department of Defence officials reported that 75% or more of the total cost for a weapons system is due to operations and support costs. While it is unclear the exact portion of the total cost of transportation infrastructure is due to maintenance and renewal costs, it is clearly substantial and thus should play a role in the design and management decision-making.

It follows that lifecycle cost and in some cases lifecycle benefit/cost analysis is a critical concept for making investment decisions, and therefore should be incorporated in the engineering and management of infrastructure systems. Several important questions remain before one may conduct a meaningful LCC analysis, however. These relate to the determination of the lifecycle of a new, maintained, rehabilitated or retrofitted structure and its expected performance along the lifecycle as affected by the Limit States listed in Table 1. The impacts of uncertainty in estimating the risk involved in establishing appropriate demand envelopes for various limit events as depicted in Figure 1 are significant for LCCA in design and in maintenance management.

An important benefit of LCCA in the case of integrated asset management is the guidance it provides regarding the integration of the different definitions and indicators of performance for different asset groups such as bridges and pavements. By adopting the lifecycle benefit/cost and in some cases lifecycle cost of any project for any asset group, whether this is a stretch of pavement, or a bridge, or signalisation and lighting of an intersection as a normalized measure for comparison, we may formulate the relative worth of any investment and this may serve as the key common denominator for integrated management of all asset groups. We should note that in this context LCCA is not serving as a decision tool by itself but is facilitating integrated AM.

5.2 Integration of Innovative Paradigms and Concepts:

The hierarchy of the paradigms and concepts that are discussed above: (a) asset management and lifecycle cost, (b) performance-based engineering, and, (c) systems-identification, health monitoring and intelligent systems is postulated in the figure. The hierarchy is based on the societal, organizational and professional buy-in required for their adoptions, respectively. We note that *adoptions in concert* are critical, as unlike other engineering disciplines, civil engineering reform cannot occur without parallel policy and legal reforms by societal institutions, especially federal and state government agencies and quasi-government organizations such as toll-road and toll-bridge managers and utilities.

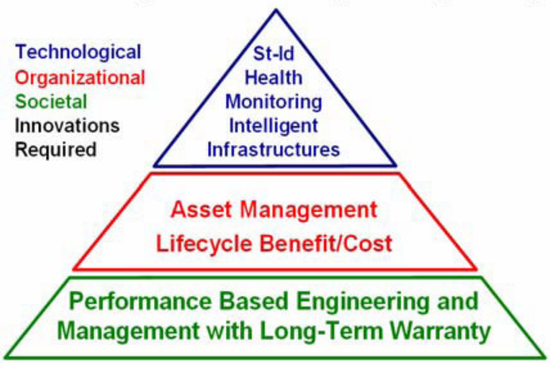


Fig. 11: Paradigms for innovation

5.3 Asset Management

The origins of AM go back to "operations research" developed during World War II, and the paradigm has been applied extensively in economics, finance and manufacturing. The authors define the goal of AM as the effective management of large and complex systems in an integrated manner, through explicitly considering the dynamic interactions between all of the heterogeneous elements within the system. As such, AM aims to provide information about the trade-offs associated with various decisions, which can be used as a basis for reconciling many conflicting objectives and constraints, with the aim of enhancing system performance rather than individual performances of elements. The first application of AM to civil engineered systems, termed "Applied Systems Analysis," was pioneered by de Neufville (1990) who subsequently demonstrated how this concept may help enhance the design and optimise the operations of airports (2003).

Table 1 - Limit states, limit events and performance goals

Limit State	**Life Cycle Utility, Functionality, Sustainability**	**Serviceability and Durability**	**Life Safety and Stability of Failure**	**Substantial Safety at Conditional Limit States**
Limit Events	Environmental impacts and sustainability	Excessive: Displacements, Deformations, Drifts	Excessive movements, settlements, geometry changes	Lack of multiple escape routes in buildings
	Societal impacts	Deterioration	Material failure	Lack of post-failure resiliency leading to progressive collapse of buildings, bridges
	Functionality throughout the life cycle	Local damage	Fatigue	
	Financing mechanisms for initial and life cycle costs	Vibrations	Local and member stability failure	Cascading failures of interconnected infrastructure systems
	Operational capacity, safety, efficiency, flexibility and security	Lack of Durability (Special limit state that should govern aspects of global design, detailing, materials and construction)	Stability of Failure (Incomplete and premature collapse mechanism(s) without adequate deformability and hardening)	Failures of Infrastructure elements critical for emergency response medical, communication, water, energy, transportation, logistics, command and control
	Feasibility of construction, protection and preservation			
	Aesthetics		Undesirable (sudden, brittle) failure mode(s)	
Goals	Constrained multi-objective performance function for integrated asset-management (Functions relating to operations, security and lifecycle cost)	Constrained multi-objective performance function for integrated asset-management (Functions relating to inspection, maintenance and lifecycle cost)	Multi-hazards risk management (Assurance of life safety and quick recovery of operations during days-months that follow an extreme event)	Disaster response planning, and Emergency management (protection of escape routes, evacuation, search and rescue needs, minimizing casualties and economic recovery within years)

6 PRACTICAL IMPLEMENTATION

The procedures to be taken within the Decision Support System depend on the boundary conditions of its use. It is important that a clear specification is found for the activities, the targeted users or the expected impact. In the following these are categorized.

Impact on (relevant on):

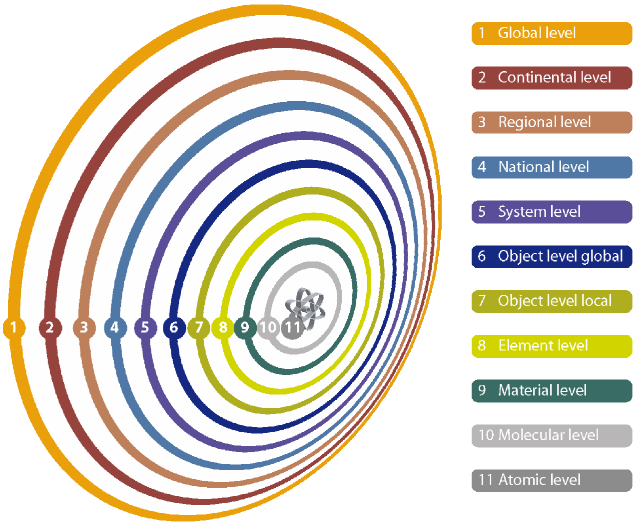


Fig. 12: Impact levels

In general it has to be stated that clients need and desire a support of their work and not issues that makes it more complicated. In this respect also the procedures have to be carefully watched and permanently improved. The information policy also plays a major role in the client - consultant relationship. The new methodologies are rather complex and require a deep understanding of structural dynamics, physics and measurement techniques. Due to the fact that this expertise is rarely available at the owners engineering department, the fear to be exposed to unknown black box applications has to be taken from their shoulders. On the other hand they are spending considerable amounts of money and would like to be informed frequently about progress and results. Therefore we have to ensure them that the technology part is in good and competent hands and that they will receive the necessary information they desire. The best success has been achieved with very simple reporting techniques. A periodic report received by email comprising single page information is preferred. The main information is provided in a single window, where upper and lower normalized thresholds are given and the measurement results within this period are placed within these thresholds. With one look at this graph the personnel can immediately see whether any of the thresholds has been exceeded. The client is satisfied because all indicators are green and the ordered observation is permanently working.

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