SAFETY AND TRANSPORT
SAFETY

Inspection and monitoring of bridges in Sweden

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BIG BRO

Abstract

This report provides an overview about recent research activities and current practice concerning inspection and monitoring of the structural performance of bridges and the related decision-making process. A brief review of common methods of collecting information on structural performance of bridges is presented, followed by a description of the use of the information collected in structural analysis and maintenance planning. An overview about the state of the art is given including recent scientific developments. Finally, the current Swedish practice for bridge management is presented.

Key words: condition assessment, inspection methods, structural health monitoring, bridge maintenance

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Preface

The report has been prepared as part of the BIG BRO project (*Decision support for maintenance and upgrading of existing transportation infrastructure based on advanced assessment technologies and structural health monitoring*).

The authors wish to acknowledge the financial support provided by the Swedish Transport Administration (Trafikverket), through *Branschprogram för forskning och innovation avseende byggnadsverk inom transportsektorn* (BBT), and by the strategic innovation programme InfraSweden2030, a joint effort of Sweden's Innovation Agency (Vinnova), the Swedish Research Council (Formas) and the Swedish Energy Agency (Energimyndigheten).

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Summary

The optimization of bridge maintenance requires prioritization and decisions on various possible actions which typically have uncertain outcomes. The outcome of the actions, and thus the preferred maintenance strategy, usually depends on the structural condition of the bridge.

There is a great variety of methods and tools available for condition assessment, i.e. to obtain information about the structural condition and to make use of the available information. Selecting the most efficient method is not necessarily straightforward and can be considered as part of the decision problem related to finding the optimal maintenance strategy.

The assessment procedure of existing bridges follows a successive approach, i.e. the elaboration of the assessment is gradually increased until a sound judgement about maintenance actions can be made. These actions are typically more costly than the assessment and might be associated with possibly significant consequences. The procedure involves collecting actual information by field inspections (i.e. occasionally or regularly making observations or collecting samples for further testing) and/or monitoring (i.e. installation of a continuous measurement system) of various quantities which somehow give a direct or indirect information about the structural condition.

The information to be collected by inspections can be different for bridges of different construction materials and their associated deterioration processes. Therefore, a brief overview about the inspection of bridges built with the three main construction materials (steel, reinforced concrete and timber) is given in this report, together with references for more detailed information. The main focus is on non-destructive methods due to their increasing availability and low operational impact.

To access the condition of the bridge as an entity structural health monitoring can be useful. Monitoring of bridges is a popular research topic and could focus on various aspects of structural performance. Some findings regarding these aspects are provided in this report with an emphasis on monitoring campaigns carried out in Sweden.

The information collected, either through inspection (including testing) or monitoring, is typically used to predict future behaviour of the structure for enabling the selection of the most suitable course of maintenance actions. The first part, i.e. to predict the structural behaviour of bridges (including structural response, loadings, consequences of underperformance and associated uncertainties) is discussed in a subsection on modelling and analysis; whereas the second part, i.e. how the model predictions are taken into account in selecting the best maintenance actions, is discussed in a subsection on decision making.

It is important to note that for a rational decision making, the context needs to be defined. Therefore, an overview about the current condition assessment and decision-making process is described in the report.

1 Introduction

1.1 Background

Maintenance of transportation infrastructure assets is often expensive and does not only include the direct cost of interventions, but also the indirect consequences of traffic disruptions. Since transport infrastructure is usually public, it is essential to optimize the costs of operation and maintenance of the assets. To make rational decisions reliable information about the performance of existing structures is needed, including knowledge about the anticipated demands (e.g. effects from traffic loads, environmental exposures, degradation processes) and capacity (e.g. resistance, robustness, durability).

The main purpose of the BIG BRO project is to develop a framework for a decision support methodology that can be used for implementing maintenance strategies on a rational basis. In general, the decision support could relate to both 1) the determination of strategies to be implemented or 2) the implementation of specific strategies.

The framework utilizes knowledge from different fields, such as on-site measurement technology, laboratory testing, advanced structural analysis, structural reliability, risk assessment, and decision theory. These components, necessary for the rational management of bridges, are often treated separately and might lead to suboptimal decisions when considering the overall life-cycle benefits of a bridge or portfolio of bridges. To enable rational decisions the process of obtaining and updating information about structural performance (through inspection and monitoring) and the process of making decisions based on the available information should be combined in a common decision support methodology.

The ultimate goal of the project thus is to establish, implement and demonstrate the usefulness of the decision support methodology for the maintenance of existing transportation infrastructure. To achieve this vision, the project is divided in three main stages as shown in Figure 1.

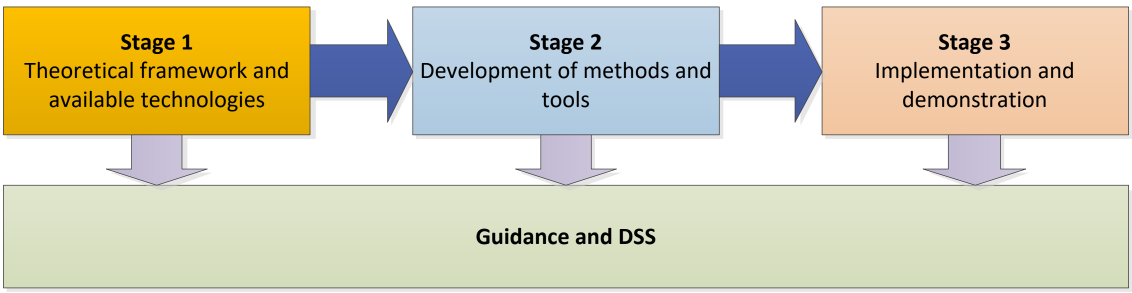

Figure 1 Stages of the BIG BRO project.

In the first stage of the project the theoretical framework is developed for the decision support methodology for the assessment, maintenance and upgrading of existing transportation infrastructure. The development requires the following main steps:

1. Understanding of what can be done, what is being done and what is needed to achieve the aforementioned goal;

2. Critically review of existing methods for testing and monitoring, structural response modelling, reliability analysis and current practice of maintenance strategies;
3. Suggesting of a theoretical framework and definition of requirements for implementation of the methodology.

The current report is related to the first two steps and serves as a critical review of the state-of-the-art (SOTA) and state-of-the-practice (SOTP) to support the framework development.

1.2 Objectives

To provide a relevant SOTA and SOTP for the development of the methodology the objectives of this report are to:

- Review the current practice and needs of structural performance assessment e.g. through inspection, monitoring and advanced structural analysis;
- Review existing techniques for condition assessment (through inspection and monitoring) with the purpose of updating the reliability in connection to modelling and updating the structural models;
- Review existing structural analysis methods for evaluation of structural response and performance, in particular the use of finite element (FE) modelling techniques
- Review existing methods for evaluation of bridge specific loads or exposure;
- Review existing reliability and risk-based assessment methods for performance evaluation of bridges;
- Review relevant decision theories in view of their application to structural condition assessment;
- Describe the current decision-making process in Sweden.

2 Structural performance of bridges

2.1 Maintenance

All infrastructure managers must deal with issues regarding degradation and maintenance needs of their assets. Several strategies exist aiming to optimise resources spent on maintenance of technological systems and civil infrastructure. Moubray (1997) defines three generations of maintenance of industrial systems, i.e. corrective/ breakdown maintenance, preventive maintenance, and predictive/condition-based maintenance (see Figure 2). Figure 2a describes the goals of the different strategies, whereas Figure 2b lists tools available for achieving those goals.

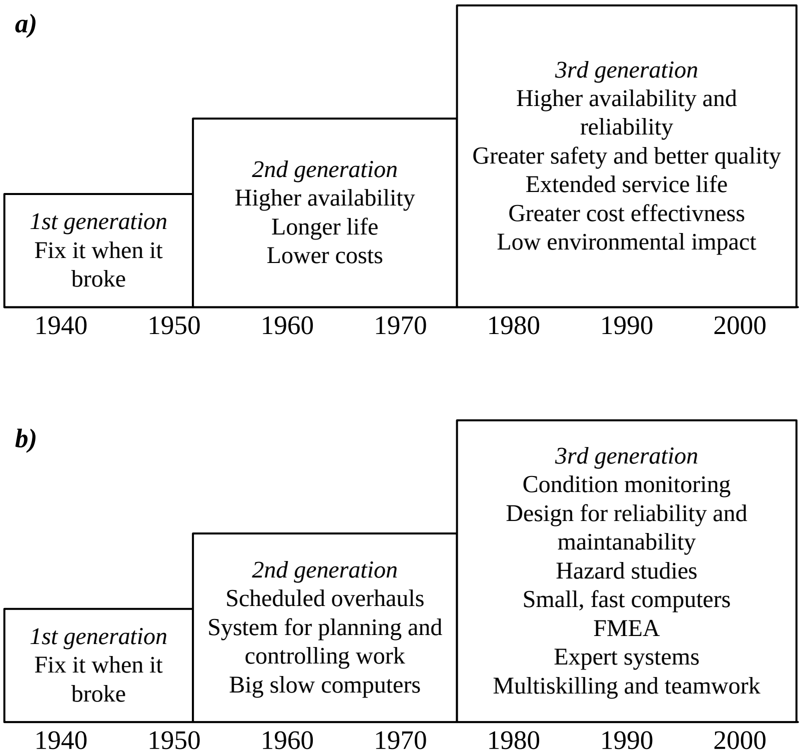

Figure 2 Three generations of maintenance (Moubray, 1997).

Maintenance of civil infrastructure is, however, notably different from that of traditional industrial systems due to two main reasons (Del Grosso, 2010):

1. Significantly longer operating life of civil infrastructures (typically several decades) leading to almost unpredictable and uncontrolled degradation;
2. Substantial differences between as-designed and as-built states due to complex phenomena governing structural behaviour of civil infrastructure.

Therefore, the actual ("as-is") state of civil infrastructure, including bridges, is at some extend unknown. To gain more knowledge about the true state, information needs to be collected (and managed).

2.2 Condition assessment of existing bridges

Several frameworks for the assessment procedure of existing bridge structures have been developed in various research projects (e.g. BRIME 2001, Sustainable Bridges 2007a). These are usually based on the procedure proposed by Schneider (1997) which has been adopted e.g. by the JCSS and RILEM (JCSS, 2001), and more recently by ISO 13822 (ISO 2010). The ISO 13822 procedure is presented in Figure 3.

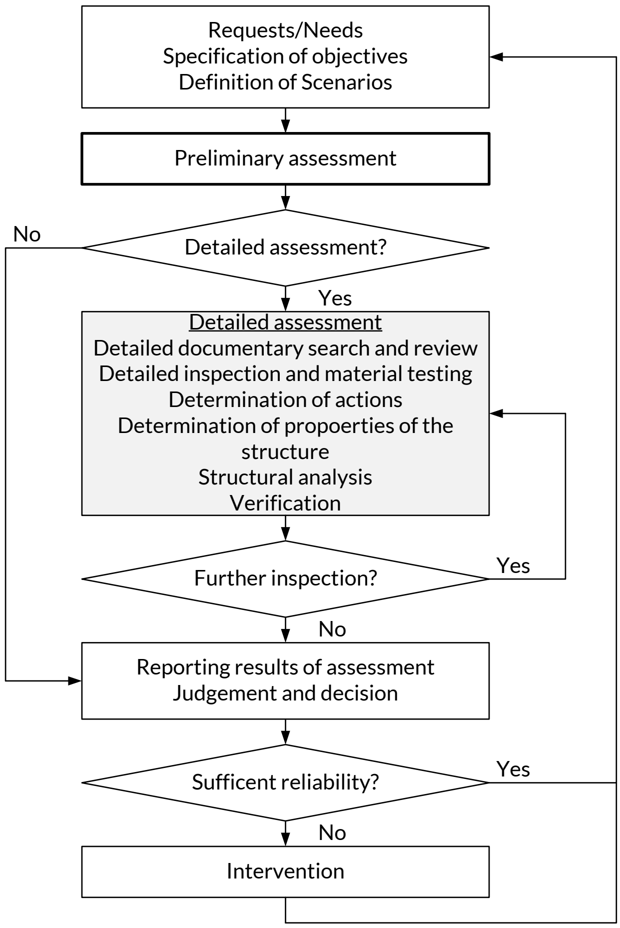

Figure 3 The ISO13822 procedure for condition assessment (ISO, 2010).

These procedures usually include the following main steps:

1. Identification of the need for assessment due to e.g. regular inspection, doubts about performance, change in requirements;
2. Preliminary assessment (document search, simplified analysis, visual inspection) and evaluation of results;
3. Decision on further assessment;
4. Detailed assessment if needed, including e.g. material testing at critical sections, detailed structural analysis, reliability analysis;
5. Decision on further assessment and possibly go back to step 4;
6. Reporting of the results;
7. Decision on maintenance actions; and
8. Intervention (if needed).

The condition assessment process thus includes a decision on if further detailed assessment is needed. Usually the level of detailed assessment is gradually increased before interventions take place. How the level of assessment should be increased is not obvious.

2.3 Condition of new bridges

To ensure that structures achieve the required quality and performance through the expected life cycle is a fundamental task where each phase of the project plays a very important role. Conceptual design decisions need to be based on both theory and experience, to minimize risks and guarantee optimal results.

Exhaustive resources regarding calculation methods, material behavior and structural design can be found in the literature, however good documentation practices regarding execution and maintenance phases are still scarce and poor. The development of good documentation practices are vital, especially in times where technology plays such an important role and is a powerful tool on this matter. Furthermore, documentation provides the basis for preliminary assessments if doubts about the sufficiency of structural performance arise. Hence, an informative and easily accessible documentation can increase the credibility of initial investigations and the subsequent detailed assessment process.

Taking part of the available technology and following the markets demand, the concept of Birth Certificates has been introduced as an initial step of conservation management of concrete structures (fib, 2012; Matthews et al. 2013). The main idea behind the concept is to provide a better documentation of the construction phase of the project and to keep track of changes that can be crucial for the decision-making process related to maintenance and risk assessment of structures. As described in the model code, the birth certificate of a structure should provide details on important parameters concerning durability, service life details and all the ground information on which future decisions should be based on.

Biological actions, bearing information, design basis, specification of the different variables involved in the project and the analytical model, are some of the information that will compose the birth certificate of a structure. The document consists of a report containing formal information defining the conditions of the structure during construction phase and its state after construction. The real value of such information, however, is not easy to quantify.

3 Methods of collecting information

To collect and manage data from inspections and condition assessments, most bridge owners have their own management system. The Swedish Transport Administration (Trafikverket), for example, have developed their own system BaTMan which is used also by several city and harbour authorities. A brief description of BaTMan is provided in Section 5. Examples on other systems and tools used in Europe can be found in e.g. Helmerich et al. (2008).

BaTMan and other bridge management systems are tools for handling a vast amount of data. What is stored and made available depends on the operators and the methods used for data collection. In Trafikverket (2015), the property to measure is described in detail dependent on structural parts and material. However, the actual method to be used is not described. Commonly used methods are treated in the following sections.

3.1 Classification of methods

There are many techniques and approaches available for the condition assessment of civil engineering structures. According to ISO 13822 (ISO, 2010), assessment of existing structures includes various activities as shown in Figure 4. The main activities related to collecting information (and discussed in this section) are highlighted in the figure.

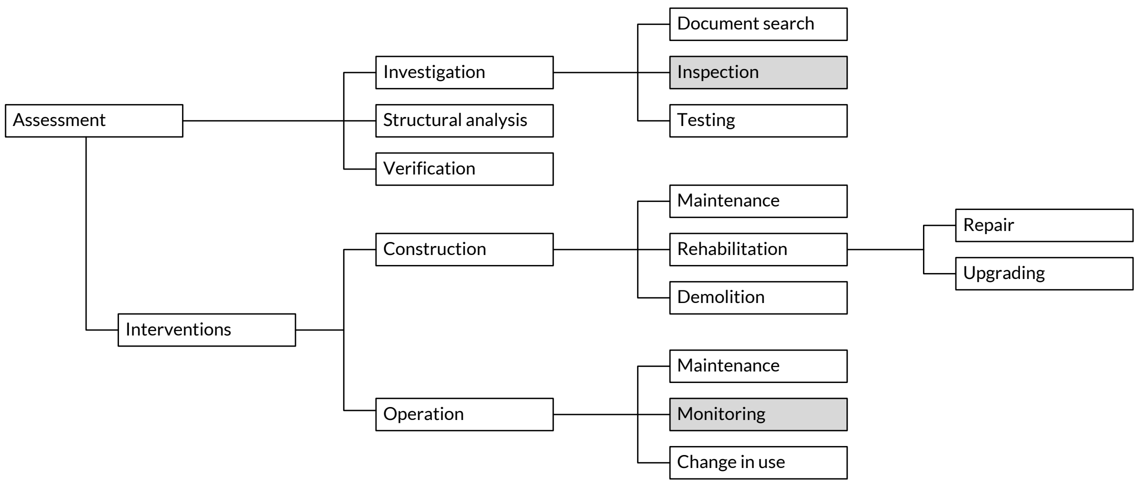

Figure 4 Hierarchy of terms related to assessment of existing structures form ISO 13822 (ISO, 2010).

In the final report from the pan-European research project Sustainable Bridges, the collecting of information is divided between regular inspection, special inspection, tests, and structural health monitoring (Sustainable Bridges, 2007a). In the report by Ahlborn et al. (2010), inspections, testing and monitoring are all incorporated into the concept of structural health monitoring.

In the current report, we distinguish between *inspections* and *monitoring* as two major methods for obtaining information as a basis for condition assessment with the major difference being how data is collected and used. Various types of inspections include visual inspections, non-destructive and destructive testing (typically of structural elements). The methods for performing these actions are usually different depending on the material as well as the degradation processes for the structure being assessed. In monitoring, the focus is usually on in-situ monitoring using sensors, and the main concern is the general structural behaviour of the bridge. Measurements of strains, displacements, accelerations, temperature etc. can be performed on any structure irrespective of the material type. However, some measurements could be better suited for specific materials or structural types. The aim of monitoring can also be to more accurately evaluate the loading, or more generally the exposures, which affect the bridge; e.g. bridge-weight-in-motion (B-WIM) systems for traffic load measurements which are mentioned in Section 3.3.1.

In this report, a classification of methods according to Figure 5 is used. In the sections that follow, a state-of-the-art review is provided by describing first (material specific) inspection methods and then (general) monitoring methods.

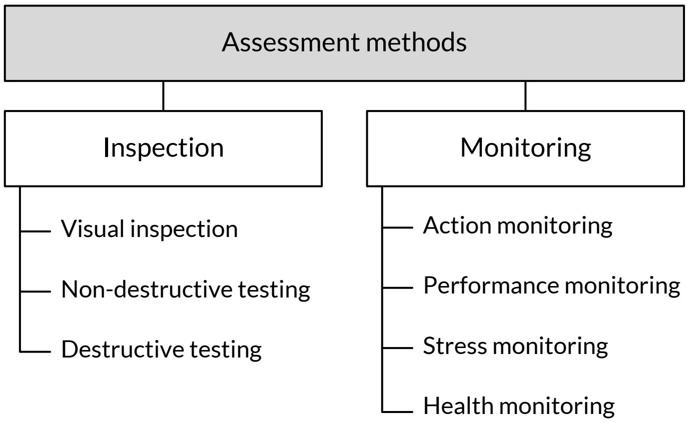

Figure 5 Classification of assessment methods.

3.2 Inspection

The inspection of bridges can be performed at different levels (Wenzel, 2009). The first level is the regular, usually visual, field inspection, also called rating. It provides a qualitative (or semi-quantitative) and rather subjective description about the structural elements and/or the structure itself. The results often provide input data for the bridge management systems and are used for prioritisation of actions. Rating based on visual inspection tends to be conservative, i.e. underestimates the remaining service life of damaged elements. On the other hand, some defects remain undetected by inspection on this level.

The next level is a more detailed assessment of the parts which are found problematic at the point of initial inspection. This usually involves some kind of calculation to better quantify the effects of the damage on the structural performance.

According to Wenzel (2009) a further level is when the performance of the entire bridge is assessed based on thorough instrumentation and detailed modelling, which in this report is discussed under monitoring.

As mentioned before, in the proposed classification, inspection activities focus on local assessment and in a large extent depend on the applied construction materials and related deterioration mechanisms. Therefore, in the following subsections, an overview about the inspection of bridges of the three main construction materials is given.

3.2.1 Steel bridges

The main causes for degradation of steel bridges are corrosion, fatigue cracking, overloading, collision damage, heat damage and paint failure (Ahlborn et al., 2010). In addition, loose connections and brittle failure are mentioned in Sustainable Bridges, (2007c). Among these, fatigue cracks are considered to be the most difficult defect to detect. The fatigue deterioration is the initiation and propagation of a crack, which is typically very small during a large portion of the service life. The propagation accelerates towards a critical crack size which defines the failure of the component. For bridges, the consequences of failure are typically high with large risks to human lives, society and environment. This entails a need for high safety requirements meaning that the allowable crack size must be kept small in comparison to the critical crack size. This puts high demands on the accuracy of the inspection methods. Furthermore, small cracks can be hidden between layers of plates or paint.

For new steel structures, non-destructive testing (NDT) is required of the welds at the construction stage (EN 1090-2, 2016). Methods to be used and the scope of inspections are specified in detail. For existing structures, methods of inspection are not at all as thoroughly specified. One reason is that the responsibility of the inspections is laid on the contractor when new bridges are built, while inspections of existing structures are the responsibility of the bridge manager. Another reason is that inspections of existing structures have to be adapted to site specific conditions.

Established inspection methods available for new as well as existing steel bridges are listed in Table 1, reproduced after ISO 17635 (ISO, 2010).

Table 1 Inspection methods for steel bridges.

Testing method	Abbreviation
Eddy current testing	ET
Magnetic particle testing	MT
Penetrant testing	PT
Radiographic testing	RT
Ultrasonic testing	UT
Visual inspection	VI

For detection of corrosion of steel members and critical details, visual inspections are often sufficient. To measure the remaining thickness of corroded components, ultrasonic inspection (UT) is recommended in Sustainable Bridges (2007c).

For detection of surface cracks, visual inspection (VI) using a pocket lens is suggested in Trafikverket (2015). However, as shown later in this section the probability of detecting small cracks by VI is small. All methods listed in Table 1 are, according to Sustainable Bridges (2007c), applicable for detection of surface cracks and weld toe defects. For hidden defects or cracks at weld roots, RT or UT are suggested.

A practical example is the Söderström Bridge, a railway bridge in Stockholm, where magnetic particle testing (MT) has been used to find surface cracks. Eddy current testing

(ET) has been used to find cracks hidden under the paint. However, the latter method is not recommended in Sustainable Bridges (2007c) for hidden cracks.

Another example is the Bridge at Hammarby Backe, owned by the Stockholm County Council (SLL), where magnetic particle testing (MT) and ultrasonic testing (UT) have been used to find cracks and weld defects. UT has also been used to measure the actual thicknesses of the members.

For fatigue, a theoretical assessment based on fracture mechanics allows an updating of the estimated reliability by considering results from inspections. One possible outcome is that a crack is detected, and the size is measured. Another is that no crack is detected. Solutions to consider both outcomes are suggested in, e.g., Madsen et al. (2006).

The most common and preferred outcome of an inspection is that no crack is detected. The updating of the probability of failure can then be expressed as a conditional probability using Bayes' Theorem:

$$P_{\mathrm{f}}^{\mathrm{U}} = P[g(\mathbf{x}) \leq 0 | H_{\mathrm{D}}(\mathbf{x}) \leq 0] = \frac{P[g(\mathbf{x}) \leq 0 \cap H_{\mathrm{D}}(\mathbf{x}) \leq 0]}{P[H_{\mathrm{D}}(\mathbf{x}) \leq 0]} \tag{3.1}$$

where $P_{\mathrm{f}}^{\mathrm{U}}$ is the updated probability of failure, $g(\mathbf{x})$ is the limit state equation based on the stochastic variables in the vector $\mathbf{x}$, and $H_{\mathrm{D}}(\mathbf{x})$ is a detection event that can be expressed as:

$$H_{\mathrm{D}}(\mathbf{x}) = a(\mathbf{x}, N_i) - a_{\mathrm{d}} \tag{3.2}$$

where $a(\mathbf{x}, N_i)$ is the estimated crack depth at N cycles and a_{d} is the lower level detectability which is typically called the probability of detection (PoD). This stochastic variable represents the accuracy of the inspection method. Examples of distribution functions for this variable, so-called PoD curves, can be found in the literature but the validity is often questionable. DNV GL (2015) suggests a unified description of PoD curves for different inspection methods. All curves are described by the same equation:

$$PoD(a) = 1 - \frac{1}{1 + \left(\frac{a}{X_0}\right)^b} \tag{3.3}$$

where X_0 and b are distribution parameters fitted to experimental results. The curves are shown graphically in Figure 6 and Figure 7.

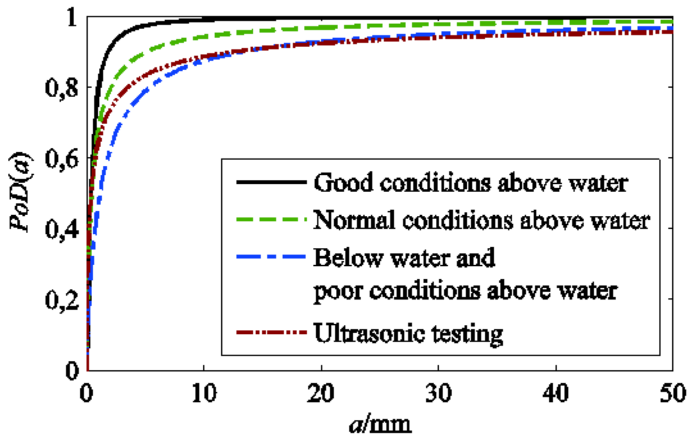

Figure 6 PoD curves for inspection methods based on ET and MT for different working conditions. A separate curve is shown for ultrasonic testing, after DNV GL (2015).

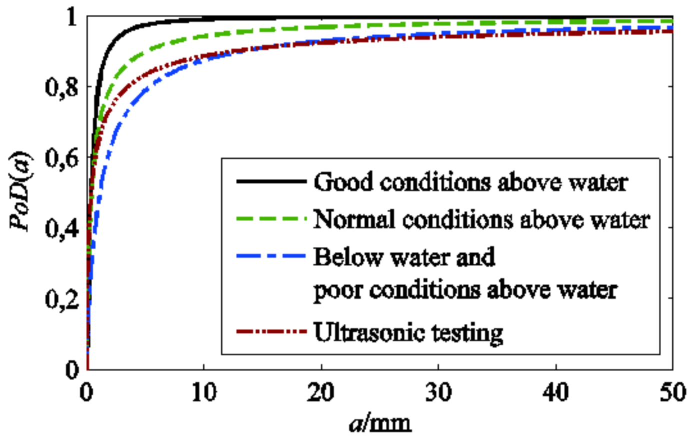

Figure 7 PoD curves for visual inspection (VT) for different working conditions. The crack depth a in equation (3.3) should be replaced by the visible crack length 2c, after DNV GL (2015).

Application examples on the procedure to update the probability based on different inspection outcomes can be found in Madsen et al. (2006) and Zamiri et al. (2016).

Destructive testing, which falls within a specific category of inspection methods in Figure 5, is typically used to obtain information about material properties. For steel the most important properties are (Kühn et al., 2008): the chemical composition, fracture toughness, yield strength, and tensile strength. The first two are useful for the interpretation of how brittle the material is, if it is prone to sudden fracture in the presence of a defect. For bridges built before 1970, Trafikverket (2016) states that the chemical composition and the toughness properties should be determined according to Trafikverket (2014). The yield strength and the tensile strength are useful in the determination of the static strength. All these material tests require that specimens are cut out from the structure and transported to a testing facility. This may cause practical problems which have to be weighed against the expected benefits.

If a damage tolerance method based on, e.g. linear elastic fracture mechanics is used for fatigue assessment, crack propagation data is needed. An extensive review of data from offshore steel structures is evaluated and presented in King et al. (1998). These values are incorporated in guidelines as BS 7910 (BSI, 2013) and JCSS (2011). Unfortunately, data for steel collected from bridges are rare. The influence of the crack growth parameters on the estimated fatigue life is shown in a sensitivity analysis presented in Zamiri et al. (2016). Large differences are attained depending on the values used. Hence, it might be rewarding to extract samples for crack growth testing in addition to conventional fracture toughness tests.

3.2.2 Concrete bridges

Despite significant advances in structural design and practice as well as maintenance and preventive strategies, corrosion in reinforced concrete structures is still a leading cause of deterioration worldwide (Jensen et al., 2007). Moreover, the corrosion deterioration is expected to propagate even faster due to the impact of climate change (Wang et al. 2010). This situation has led to a growing demand for better condition assessment of existing concrete structures and has revealed a need for an improved inspection of RC structures.

Other severe types of deterioration in concrete structures are associated with the volume expansion of concrete caused by freezing. When the volume expansion of freezing water cannot be accommodated in the pore system of concrete, it is restrained by the surrounding concrete. Thereby, tensile stresses are initiated, and micro and macro cracks are introduced into the concrete body, which leads to a type of damage known as internal frost damage. This mechanism affects the stress–strain relation in compression and tension, as well as compressive and tensile strengths, elastic modulus, fracture energy, and bond strength between the reinforcement and surrounding concrete in damaged regions (Fagerlund et el. 2001). Another type of frost damage, known as surface scaling, is caused by mechanisms involving the differing thermal expansion of ice and concrete (Valenza et al. 2006). This mechanism is involved when a concrete structure is subjected to cold climates in the presence of saline water. Beyond corrosion and freeze-thaw, other deterioration mechanisms relevant to RC structures are alkali silica reaction (ASR), chemical attack (sulfate attack and acids), as well as biodeterioration.

Inspection methods can be categorized according to the following: Visual and simple NDT, Acoustic NDT-methods, electromagnetical methods, radiography, thermography, electrochemical and spectroscopy, and measurements and minor destructive test. A number of established inspection methods for RC structures/bridges are listed in Table 2 based on Sustainable Bridge (2007d)

Table 2 Inspections methods for RC bridges.

Testing method	Abbreviation
Acoustic Emission	AE
Ground Penetrating Radar/ Impulse Radar Echo	GPR
Impact-Echo	IE
Laser-induced Breakdown Spectroscopy	LIBS
Potential Mapping	PM
Radar Tomography	RT
Ultrasonic Pulse Echo	UPE
Ultrasonic Transmission	UT
Visual inspection	VI

Visual Inspection (VI): Visual inspection is typically applied to detect contamination, material loss, deterioration, displacements and cracks. VI can be easily applied by inspectors during regular inspections and is often combined with simple NDT methods. This method is limited in the sense that it solely provides surface observations and a crack measurement accuracy limited to 0.1 mm. The duration of the inspection is highly related to the given bridge span l being investigated, e.g. l < 10m can amount to 0.5 days and l > 100m can amount to 20 days.

Acoustic Emission (AE): This acoustical test method involves a series of single sensors (minimum of 4) or an array of sensors attached to the surface. Ultrasonic signals which are released by cracking are recorded. Information, such as noise amplitude, energy, duration, and crack type (cracking, delamination, spalling) can be captured. Active cracks can be identified and localised, before their effect is measurable. The ultrasonic signal changes the runtime with increasing deterioration of the concrete. There are no signals when cracks are not active. Filtering of noise due to traffic, existing cracks, etc. is necessary.

Impact-Echo (IE): This acoustical test method makes use of an impactor that generates stress (sound) waves which propagate through the concrete surface and are thereafter reflected by internal flaws and/or external boundary surfaces having different acoustic impedances (see Figure 8). A transducer records the surface displacements caused by multiple reflections of the waves versus time. These displacement signals are subsequently transformed into the frequency domain.

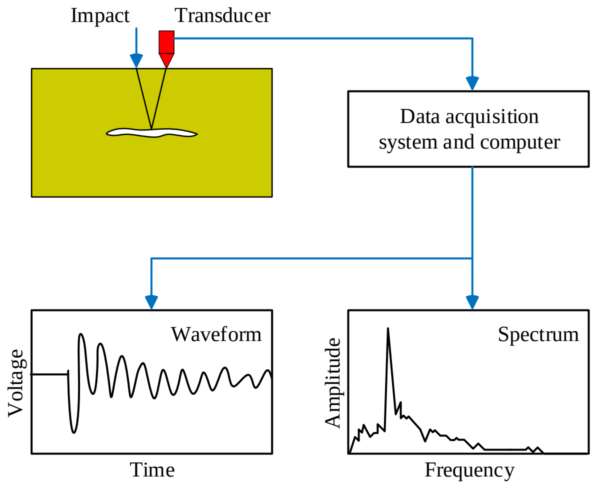

Figure 8 Simplified diagram of the IE method (adopted from ww.NDT.net).

Dominant frequencies are assigned to depth values by applying the so-called IE formula, whereby the wave speed must be determined for each concrete through calibration at a position of known thickness or by measuring on a core.

$$d = \frac{v_L}{2f} \tag{3.4}$$

where v_L is the P-wave velocity and f is the measured frequency.

Minimum detectable target size varies according to the depth of the target. It is a very effective test method for a depth from 0.1 m up to about 1.2 m. This method is typically used for thickness determination, localisation of delamination, voids, inhomogeneities, as well as hollows in tendon ducts.

Ultrasonic Pulse Echo (UPE): This acoustical technique consists of the transmission of ultrasonic-pulses into concrete which are reflected by material defects or by interfaces between regions of different densities and/or elastic moduli. A receiver coupled to the surface monitors the reflected waves. Point measurements are combined to visualise the reflection. It is worth noting that the propagation of ultrasonic waves is limited by layers containing air, e.g. concrete with large amount of air pores and by very dense reinforcing bars. This method is used for the inspection of the inner structure of structural elements made of reinforced and prestressed concrete, rebar and tendon locations, compaction faults and voids.

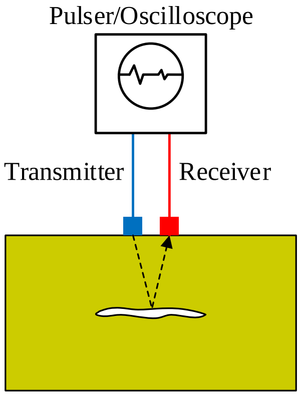

Figure 9 Simplified diagram of UPE (adopted from ww.NDT.net).

Ultrasonic Transmission (UT): This acoustical technique is often used to estimate the dynamic modulus of elasticity and is used for the quantification of frost damage. The relative transit time, γ_n, after n freeze-thaw cycles, can be calculated as:

$$\gamma_n = \frac{t_n}{t_0} \tag{3.5}$$

where t_n is the transmission time measured after n freeze-thaw cycles, and t_0 is the initial transmission time before the first freeze-thaw cycle.

Furthermore, it is convenient to express internal damage as the relative dynamic modulus of elasticity, $R_{u,n}$, from the ultrasonic transit time. Assuming that the ultrasonic transit time is inversely proportional to the fundamental frequency and that the change in the mass of concrete is negligible, the relative dynamic modulus can be calculated accordingly:

$$R_{u,n} = \frac{1}{{\gamma_n}^2} \times 100\ [\%] \tag{3.6}$$

Impulse-radar echo (Ground Penetrating Radar – GPR): This method applies electromagnetic waves by sliding an antenna over the concrete surface. It is important to note that if variation in the dielectric properties of the different materials is low, only a small amount of energy will be reflected. For example, electromagnetic waves cannot penetrate any metallic layer. The shape of the constructional elements (e.g. diameter of rebars) or material inhomogeneities are difficult or not at all possible to estimate. This method is often used for the inspection of the inner structure of structural elements made of reinforced or post-tensioned concrete and masonry, to detect and localise inhomogeneities (voids, metal or wood inclusion), thickness of structures which are only accessible from one side, internal structure of complex elements, as well as to determine the moisture content and distribution.

Radar Tomography (RT): In this approach, electromagnetic pulse is sent from one side and received on the other. Travel times and amplitude information are used to reconstruct the hidden structure and to provide velocity and attenuation distribution. The technique is used for poorly compacted concrete, high moisture and chloride content, voids greater than 100 mm. With proper calibration, RT is used to quantify the dynamic modulus of elasticity which can be used to quantify frost damage in RC structures.

Potential mapping (PM): This electrochemical method is used for the determination of defects related to corrosion of reinforcement and chemical attack (sulphate, chloride and ASR). The corrosion potential is essentially measured as the potential difference (or voltage) against a reference electrode (half-cell). Measurements related to half-cell potentials are based on the electrical and electrolytic continuity between the rebar in concrete, reference electrode on the concrete surface and voltmeter (see Figure 10). Limitations of PM are the conductive cover between reinforcement and surface, membranes, asphalt or other sealing parts.

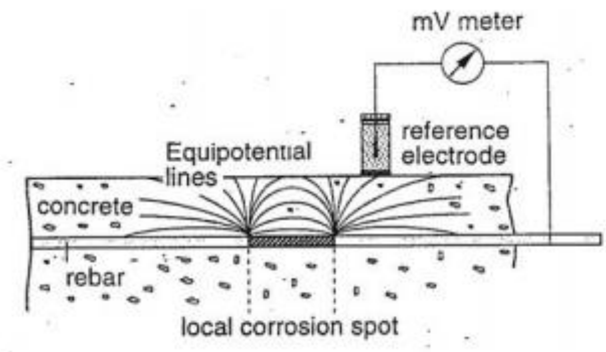

Figure 10 Principle and main components of half-cell potential measurements: Reference electrode, high impedance voltmeter, connection to the rebar. Adopted from RILEM TC 154-EMC (Elsener, 2003).

Laser-induced Breakdown Spectroscopy (LIBS): This method uses a pulsed infrared laser for plasma generation and a spectroscopic system to analyse the emitted radiation. LIBS does not require any surface preparation and rapidly allows the identification of the depth of chloride ingress in a concrete structure.

3.2.3 Timber bridges

Regular inspection and maintenance of timber bridges is essential due to their susceptibility to various types of deterioration mechanisms (biotic and physical). The exposure to unfavourable environmental events, biological degradation, weathering and mechanical damage affects the structural integrity of the structural member as well as the performance of the entire structural system (Emerson et al. 1999). Therefore, it is of great importance to identify those hot spots in an early stage.

Several methods have been developed and applied to assess structural performance causing minimum physical intrusion and disturbance to guarantee the continued function of timber bridges. Semi-destructive testing (SDT) and non-destructive testing (NDT) techniques can be employed to locate damage and deficiencies and in order to obtain further characteristics about the structural condition (Kasal, 2004). Often there is a need to combine several inspection techniques using a comprehensive assessment strategy that estimates overall effects on structural integrity. A systematic assessment strategy is valuable and effective in the evaluation of the structural condition and performance in order to preserve timber structures to the greatest extent possible.

Wood is an anisotropic material, i.e. the characteristics vary between the different directions. Furthermore, due to its natural characteristics which cannot be controlled by the production process, the material properties depend on several factors, such as e.g. wood species, moisture content and natural growth defects. In addition, the mechanical properties at element level are also influenced by the type and duration of loading and geometry of the elements (Köhler and Svensson, 2011.). This also affects the reliability of the data and it is important to remember that there is inherent uncertainty in the NDT method (Kasal, 2010). As a result, common certified standards for in-situ material testing using non-destructive tests to assign material strengths for structural assessment as accurately and correctly as possible should be established. However, current procedures and results to obtain material parameters from non-destructive testing show large variations (Feio, 2006, Íñiguez et al., 2008, Esteban et al., 2010, Machado et al., 2011). Therefore, in order to improve the accuracy of the assessment based on non-destructive testing techniques, the information needs to be cross-validated by combining non-destructive and destructive large-scale testing (Machado et al., 2011).

As mentioned before, unprotected wood is subject to different types of degradation processes. Uppal and Rizkalla (1992) divide deteriorating agents of timber structures in two main categories: biotic and physical agents. Biotic agents (fungi, bacteria, insects, etc.) are seen most dangerous for timber bridges if undetected. Biotic agents attack and decay (unprotected) wood if all four conditions for their survival are present: sufficient moisture content, enough oxygen, appropriate temperature and food (untreated wood). Physical agents include e.g. traffic, stream flows, soils, weather, corrosion (of metallic fasteners), fire etc. Besides their possible direct impact on structural safety, physical agents may also damage the preservative treatment of wood and give way to biotic attack. Usually, areas of high moisture content in the decking, girders, abutments and pilings cause appropriate conditions for biological damage such as mould, decay and insect/fungal damage. Also, mechanical damage of the timber as well as mechanical fasteners might be observed and remedied (Brashaw et al. 2013).

A variety of NDT techniques can be employed by an inspector in order to determine the condition of an aging timber bridge. To improve the prediction on timber strength and overall the structural capacity these methods are often used in combination and in sequence. The preferred test sequence, with which the different NDT methods should be applied in order to optimize the assessment, needs be investigated, since the different methods have different characteristics and suitability in relation to the type of structure being assessed. For example, when locations of suspected damage are easily accessible, a detailed investigation using the test method requiring the least effort (typically the cheapest one) is usually preferred to verify the section that has deteriorated and the extent of the deterioration and its impact on the structure (Kasal et al., 2004). However, sophisticated assessment tools might be required to detect hidden damages in timber structures.

Comprehensive inspection protocols for timber bridges include a wide variety of techniques to assess the condition of wood in service. Visual inspection, moisture content assessment, mechanical probing, drilling, resistance micro-drilling, stress wave or ultrasound-based technologies may all be used individually or in combination by inspectors. The standard equipment for efficient testing is composed of tape measure, hammer, awl for the basic inspections and a stress wave timer, resistance micro drill and a moisture meter for the more advanced/detailed investigations, see Figure 11 (Brashaw et al. 2014).

Figure 11 Inspection equipment used for inspection of timber bridges (Brashaw et al. 2014).

To obtain further characteristics of the structural elements and their performance, several semi-destructive testing (SDT) and non-destructive testing (NDT) techniques can be adopted. Here, the most common and relevant timber inspection NDT methods are shortly described. Some of established inspection methods for timber bridges are given in Table 3.

Table 3 Inspections methods for timber bridges.

Testing method	Abbreviation
Moisture metre	MM
Resistance drilling	RD
Stress-wave timing	SWT
Visual inspection	VI
X-ray	XR

Visual inspection (VI): Visual inspection is the starting point for any analysis on timber structures as it is the basis of any form of strength, performance grading on-site and a rather quick qualitative assessment of the structural integrity of individual structural members can be achieved. In practice, visual inspections are supported by local non-destructive tests for the detection damage and internal deterioration (Emerson, 1999).

Stress-wave timing (SWT): Stress-wave measurements are a simple and effective measurement technique to identify the internal soundness and condition of structural elements but also to determine the modulus of elasticity (MOE) for structural analysis. In these tests, two piezoelectric probes are used to receive the longitudinal ultrasound wave.

One-dimensional stress-wave transmission is the most commonly used technique to measure the time that is required to travel between the piezoelectric sensors (Wang et al., 2004). The one-dimensional stress-wave theory is sufficient for wave propagation in wood, where the transmission time and the density are related to the longitudinal MOE

This was verified and compared with the static four-point test and good correlation was achieved (Zombori, 2001). The static MOE is approximately 90% of the dynamic MOE (Görlacher, 1991, Ross et al., 1994) and the values are usually acquired using a linear relationship equation (Feio, 2006).

There are several key aspects that influence the travel of the stress waves in timber, namely: the effect of wood species, moisture content, temperature, biological and chemical degradation, decay, insect attacks, grain angle and measurement direction. These aspects have to be accounted and adjusted for in the evaluation and the interpretation of the results in order to determine quantitative parameters such as the MOE, as well as the qualitative parameters of structural soundness (Dackermann et al., 2014).

This technique requires an appropriate measurement strategy and approach in order to efficiently determine the structural performance of in-situ elements and successfully detect internal damage, as well as the extent of both external and internal damage. A stress wave-based condition assessment strategy of this kind is simply illustrated in Figure 12, where critical areas from the visual inspection were measured stepwise in different directions to identify decay and its extent in the structural element at different locations along the beam (Dackermann et al., 2014)

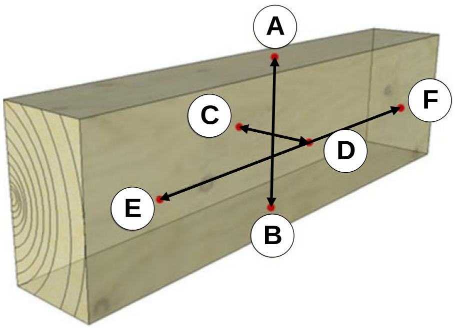

Figure 12 Measurements in different directions (A-B, C-D and E-F) to localise the extent of the damage/deterioration adopted from Dackermann et al. (2014).

The transverse propagation of the stress waves is about 25% of the value in the longitudinal direction (varying from 4,000 m/s to 5,500 m/s depending on the wood species) and it is mainly used as a qualitative parameter to assess the condition of structural elements (White and Ross, 2014). An increase in velocity sound of about 30% resulted in a loss of strength of about 50% (Ross and Hunt, 2000). A decrease in the relative velocity of less than 10% compared with the reference velocity of the specific species is an acceptable and natural variation (Dackermann et al., 2014).

Resistance drilling (RD): Resistance drilling can be used to detect and quantify the internal condition and decomposition of the wood in timber structural elements. The use of small-diameter needle-like drills was introduced by Rinn (Kasal et al., 2004). The drilling resistance is proportional to the relative variations in density, i.e. decreasing drilling resistance is followed by reduced torque in the drill. Areas that need less torque are therefore associated with reduced density.

A relatively high correlation between the drilling resistance and the density has been found by some researchers (e.g. Görlacher), but it should be kept in mind that the resistance-drilling technique has not yet provided a sufficient correlation for structures tested in situ (Kasal et al., 2004).

One of the main aspects in the use of resistance drilling is to apply appropriate drilling points and drilling direction to evaluate internal condition. The main principle is to drill perpendicularly with respect to the tree rings in order to be able to distinguish between intact wood and incipient decay from the relative density profiles (Tannert et al., 2014).

The interpretation of the density profiles from the drilling-resistance measurements often requires expert knowledge of the composition and the inhomogeneity of wood structures (Lechner, 2013). Zones of lower drilling resistance can be identified as those with lower density and vice versa. As a result, these zones usually have lower/higher strength and elasticity. Moreover, lower drilling resistance may indicate decayed zones, cavities, cracks and crevices, whereas high peaks might also indicate knots. Totally decayed wood has no drilling resistance.

Moisture metre (MM): Measurements of the moisture content (MC) with a resistive moisture meter at critical sections gives a good and fast indication over the risk of biological degradation.

A more elaborate measurement method to track the condition of a timber bridge is to continuously measure the moisture content with a remote data transmission system to assess the condition over time, to identify moisture changes, dimensional changes and internal stresses caused by the change of moisture. The main advantage though is that an early stage damage can be recognized and then the structural integrity monitored in order to prevent further deterioration (Tannert et al., 2014).

X-ray investigations (XR): X-rays are short-wave electromagnetic radiation rays that depend on the mass density variations and the thickness when they penetrate an object. The primary benefit when using X-rays is the opportunity to determine the condition of structures on site without disturbance (Anthony, 2003). A low voltage/energy X-ray powertool can be used for the in-situ investigation of e.g. timber bridges of hidden defects and integrity of the structure, see Figure 13.

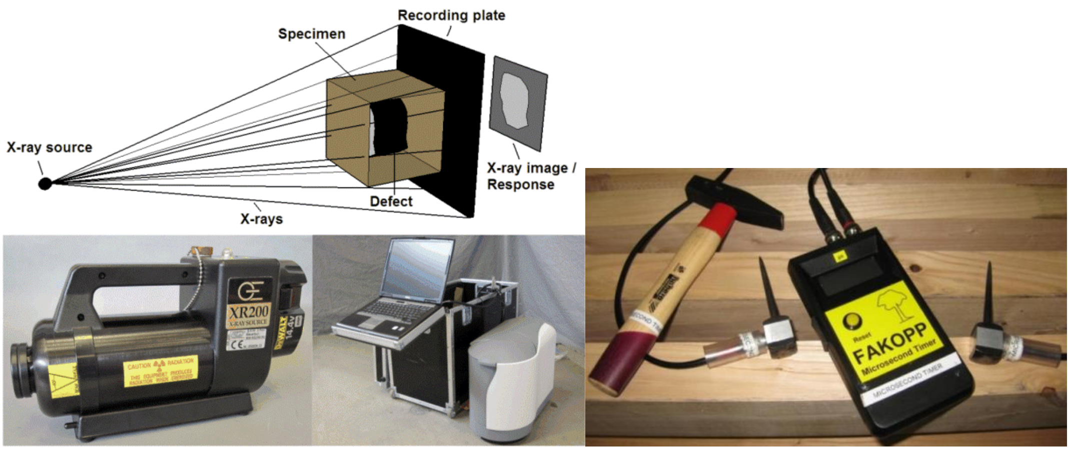

Figure 13 Example of X-ray system and recording process (Lechner, 2013).

An overview of possible applications using X-ray equipment for the evaluation of timber structures is listed (Lechner, 2013; Anthony, 2003; Lear, 2005):

- Material loss quantification due to insect attack/decay;

- Corrosion detection (of metal fasteners);
- Cross section reduction;
- Integrity/failures of mechanical connections;
- Density identification;
- Mapping damage.

As with any other method, X-ray investigations should be combined with other NDT/SDT methods though it should not be used in the initial investigation since it is not as efficient as the other tools presented above. It should be used in a detailed investigation process after a first evaluation.

Further testing methods: Further useful NDT/SDT methods, for example, are listed in Tannert et al. (2014) and include: acoustic emissions; core shear testing; core drilling: optical scanning; pin pushing/driving: surface hardness measurement; screw withdrawal resistance; thermography; videoscopy; ultrasonic pulse echo.

3.3 Monitoring

Non-destructive inspection of individual members provides valuable information about the localized condition of bridge elements, but more information is generally required for detailed assessment of a bridge as an entity.

Monitoring is typically implemented when theoretical investigations are insufficient to explain or resolve a specific issue with an existing structure. It is as yet not an established method in conventional bridge assessments. The use of monitoring in practice is a choice of the bridge owner and can be a question of opinion and resources. Furthermore, there is limited guidance on the use of monitoring techniques in modern codes for bridges. However, the Swedish code for assessment of existing bridges (Trafikverket, 2016) provides some guidance for determining appropriate monitoring actions; e.g. it allows the use of measured stresses for fatigue assessment.

In research, monitoring is an established tool and several international projects have addressed the challenges and opportunities of monitoring bridges. Guidelines and recommendations can be found in, e.g. Sustainable Bridges (2007b) and Sedlacek et al. (2007). In the latter, monitoring approaches have been divided into the following categories:

- Action monitoring,
- Performance monitoring,
- Stress monitoring and
- Health monitoring.

Action monitoring is described as the assessment of a structure's response in time and space due to a known load and/or studying the loading itself. Often the loads are not known precisely, only their main characteristics, therefore both the actions and the structural response are monitored. The purpose may be to update uncertain parameters in a theoretical structural analysis or to determine the actual loads acting on the structures using a calibrated measurement system. Performance monitoring, on the other hand, allows an assessment of whether a structural component meets the performance requirements under a known or any load. In this case, the measurements are used directly to verify the performance of the bridge or a component. The third approach, stress monitoring, allows an assessment of the state of stress in a structure or a structural component. This can be used to reduce the uncertainties in the loads and the structural behaviour or both. A specific example includes fatigue assessment of steel structures based on monitored responses. Finally, health monitoring provides real time information for the assessment of the safety and serviceability of a structure or structural components. It is founded on the condition that a sufficient number of measurable health indicators exist and can supply relevant information on the state of the structure.

In the literature, the denomination *structural health monitoring* (SHM) is often used without distinguishing between the monitoring concepts listed above. This may cause some confusion when procedures for, e.g. performance monitoring and health monitoring are used simultaneously. While the three first categories of monitoring approaches are relatively well established health monitoring is still a field of intense research. A recent contribution by Gonzalez and Karoumi (2015), e.g., proposed a model-free method for damage detection based on machine learning.

In the following sections some applications of action monitoring and stress monitoring are described. These two categories of monitoring approaches are considered to be most suitable in combination with theoretical assessments. In action monitoring, the load (or at least its characteristics) is known and can be described using theoretical models. This makes it possible to update the model against the measured response and reduce uncertainties related to the structural behaviour or severity of loading. Stress monitoring provides information about the behaviour of the structure in service, for real traffic and an assumed linear elastic response. Uncertainties regarding loads and the structural response both can, thereby, be reduced in the theoretical assessment.

3.3.1 The use of action monitoring

There are numerous examples on the use of action monitoring to investigate the behaviour of structures subjected to loads with known characteristics. Some Swedish bridges worth mentioning include the New Svinesund Bridge (Karoumi et al., 2009a), the High Coast Bridge (Karoumi et al., 2009b) and the Götaälv Bridge (Leander et al., 2015). The purpose is typically to attain basic data for updating theoretical models.

The updating can be performed by optimizing some objective function to reach estimates of the model parameters, see e.g. Schlune et al. (2009). Another method based on statistical falsification is suggested in Goulet and Smith (2013). This method can be used to derive statistical distribution functions for the model parameters. A third alternative is to use data from monitoring in a Bayesian updating of prior estimate of the reliability, see e.g. Strauss et al. (2008).

Modal analysis is typically used to examine mode shapes of the vibrating structure and compares it either to previous experimental vibrational data on the structure or to data predicted by numerical modelling. Differences in dynamic characteristics can be used to diagnose damage in the structure (Emerson et al., 1999). Another use of analysing dynamic response could be e.g. to determine dynamic amplification factors for traffic loads, see e.g. Wipf et al. (1996), Ritter et al. (1995) and Horyna et al. (1996).

When monitoring e.g. timber bridges the main focus is often not only on mechanical actions, but environmental exposures, such as relative humidity and temperature. The moisture content of the wood at different depths is measured, since moisture and temperature conditions are highly relevant for biological deterioration processes. The purpose of the measurements is often to verify models for prediction of long-term durability based on periods of surface wetting, on moisture conditions related to climatic loads, coatings, wood processing etc. (Sandberg et al., 2011).

Action monitoring can also be used for determining more accurately the loads acting on the structure, such as traffic or temperature, and to update load models used for design and verification. Traffic loads are often measured using so called weight-in-motion (WIM) techniques, see e.g. Al-Qadi et al (2016), where the axle load can be measured for each vehicle. For bridges, B-WIM measurements are continuously made by Trafikverket. Using this specific method, the response of the bridge is coupled to the weight of the passing heavy vehicle using a calibrated measurement system, and total load level, speed and axle load may be obtained. For other loads such as temperature, standard temperature measurements may be performed in, on or near the structure and used in modelling coupled with the surrounding environment, see e.g. Karoumi et al. (2009a); Larsson and Karoumi (2011).

It should be noted that even diagnostic static load tests can be seen as a basic type of action monitoring, even if a “real” continuous monitoring system is not implemented. Static load applied to a bridge provides valuable insight into the true elastic behaviour of the structure being used for assisting in the prediction of the maximum capacity (Emerson, 1999).

3.3.2 The use of stress monitoring

In contrast to action monitoring, the outcome of stress monitoring is typically used directly in a structural assessment without any intermediate interpretation using a structural model. The measurements are performed during in-service conditions with unknown loads and, preferably, over a long period of time. In Leander et al. (2010), e.g. the outcome of a stress monitoring campaign has been used for a deterministic fatigue assessment. Data from the same campaign have also been used in a reliability-based assessment presented in Leander et al. (2015).

A combination of different sensors in a comprehensive monitoring system, i.e. continuous measurement of e.g. accelerations, displacements, strains, moisture contents and weather data could be useful to verify the structural design and the long-term behaviour of the timber bridges (Björngrim et al., 2011).

4 Utilisation of data collected

The information collected through inspection and monitoring is valuable only if used to gain better knowledge about the real behaviour of the bridge in question (including the loads acting on it) and ultimately if it helps support making better decisions concerning operation and maintenance.

In the following sections we discuss questions related to:

1. Modelling and analysis, i.e. the use of information to describe and predict the performance of bridge structures and/or the actual loads;
2. Decision making, i.e. how the model predictions are taken into consideration in real-life decisions.

4.1 Modelling and analysis

Modelling and analysis in structural engineering often involves determining how a structure responds to mechanical loading or other type of exposure affecting the structural behaviour. Generally, the aim is to evaluate or verify satisfactory performance; either in terms of function or safety. The suitability and accuracy of the modeling approaches is intimately connected with the availability and utilization of information. In the sections that follow, three main aspects of modeling are discussed in relation to the utilization of the data collected e.g. using the methods described in previous sections.

The first aspect is the structural analysis using a structural model to describe the relationship between various loads (or more generally exposures) acting on the structure and the structural response of the bridge. This is essentially a sort of mapping between load and response which depends on the characteristics of the materials, geometry and boundary conditions. The data collected on structural behavior is useful for more accurately determining the condition of the structure and for updating the structural model.

The second aspect of modeling which is important to consider is the load, or more generally exposure, acting on the structure. The severity of loading can e.g. be prescribed using conservative design values or based on data collected on actual loads. The data collected about loads acting on the structure may be used either in relation to the structural response of a specific bridge, or to update load models that can be used for design and evaluation.

The third aspect of modeling concerns considerations of risks and uncertainties. Both the actual behavior of the structure as well as the loading thereupon are uncertain. Furthermore, verifications of satisfactory behavior can depend upon the severity of consequences of possible damages or failures to the structure; i.e. more critical elements have higher requirements in terms of structural safety. In general, verification procedure using a specific structural model and load can be carried out with varying degrees of consideration towards risks and uncertainties.

4.1.1 Structural response modelling

Common structural assessment strategies are based on the principle of successively improved evaluations of the structural condition (Sustainable Bridges, 2007c). In Figure 14 a flow diagram for the assessment process is explained (Plos et al., 2017). It can be seen as further development and application of the scheme in figure 3. It starts with a need for an assessment due to change of the requirements, deterioration of or damage to the structure. First of all, an initial assessment based on a site visit, a study of the documentation and analysis using simplified methods should be carried out. If the requirement is not fulfilled, an economical and sustainability decision analysis may be carried out to determine if the assessment should be continued. A continued assessment can include an enhanced evaluation with improved information (inspections, monitoring and testing), as well as improved analysis (structural analysis, resistance models and reliability-based assessment). If the assessment is not continued, the bridge may be demolished, strengthened or get a redefined use with e.g. reduced loads. An enhanced assessment can result in a decision whether it is possible to continue using the bridge, possibly after strengthening, repair or redefined use, or whether it may be used under intensified monitoring.

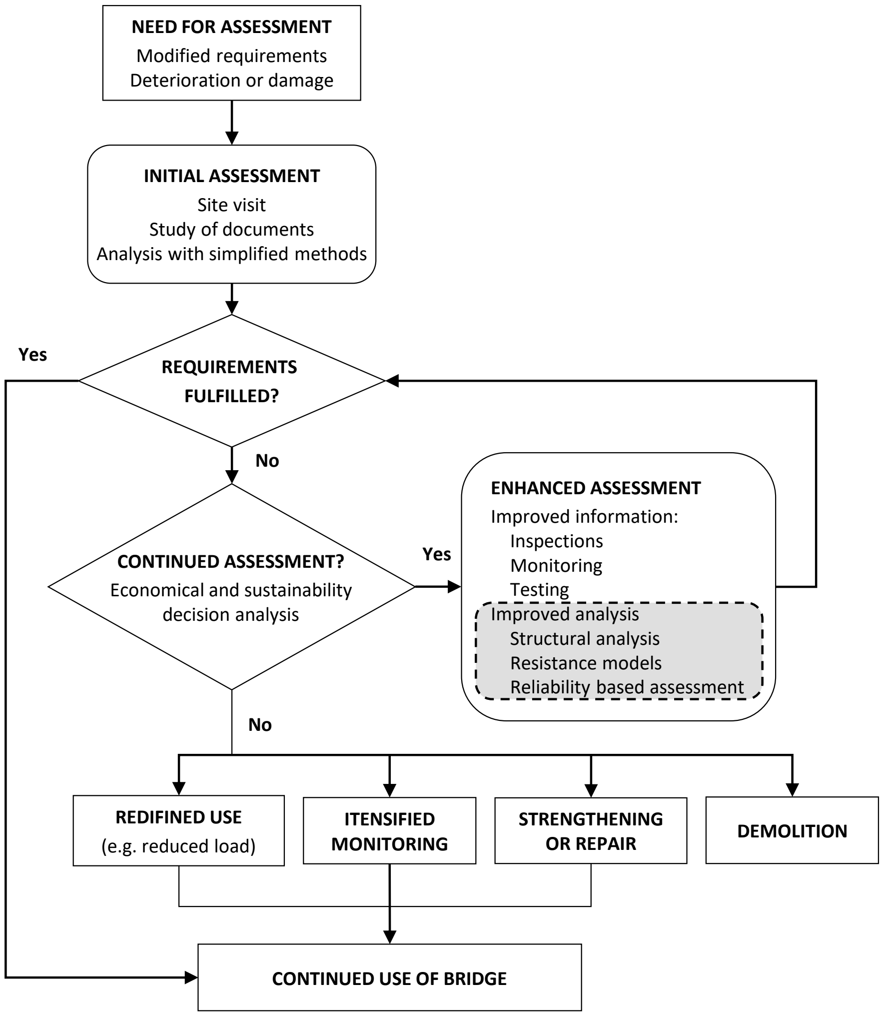

Figure 14 Flow diagram for condition assessment based on the principle of successively improved evaluation (Plos et al., 2017).

Since the traditional structural analysis method may be too conservative in assessing the load carrying capacity of bridge components or of the system as a whole, advanced analysis methods can be used. Such methods can lead to a better understanding of the structural response and reveal higher load-carrying capacity.

Today, 3D linear FE analyses are commonly used in engineering practice. In research, non-linear FE analysis is a standard method for better understanding of structural response and estimation of load-carrying capacity. However, in engineering practice non-linear methods are, despite their documented potential, still used to a very limited extent. One reason for this is that there is not much literature available to provide practical recommendations. Nevertheless, Hendriks et al (2017) provides guidelines for non-linear FE analysis of RC members and Broo et al. (2008) presents a guide to the non-linear FE analysis of shear and torsion in concrete bridges.

To provide a better structure for enhanced assessment, a multi-level assessment strategy has been proposed in Plos et al., 2017 and presented in Figure 15. The proposed assessment strategy focuses on enhanced assessment through improved structural analyses and resistance evaluations. The general idea is based on the principle of successively improved evaluation in structural assessment (Sustainable Bridges, 2007e) and the level-of-approximation approach in MC2010 (fib, 2013). Higher level methods can be used in cases where higher accuracy would be required, as presented by Belletti et al. (2014) who found that by increasing the level of approximation, the design load obtained would increase as well. Such higher levels generally require greater effort but may lead to more economic solutions (Plos, 2002).

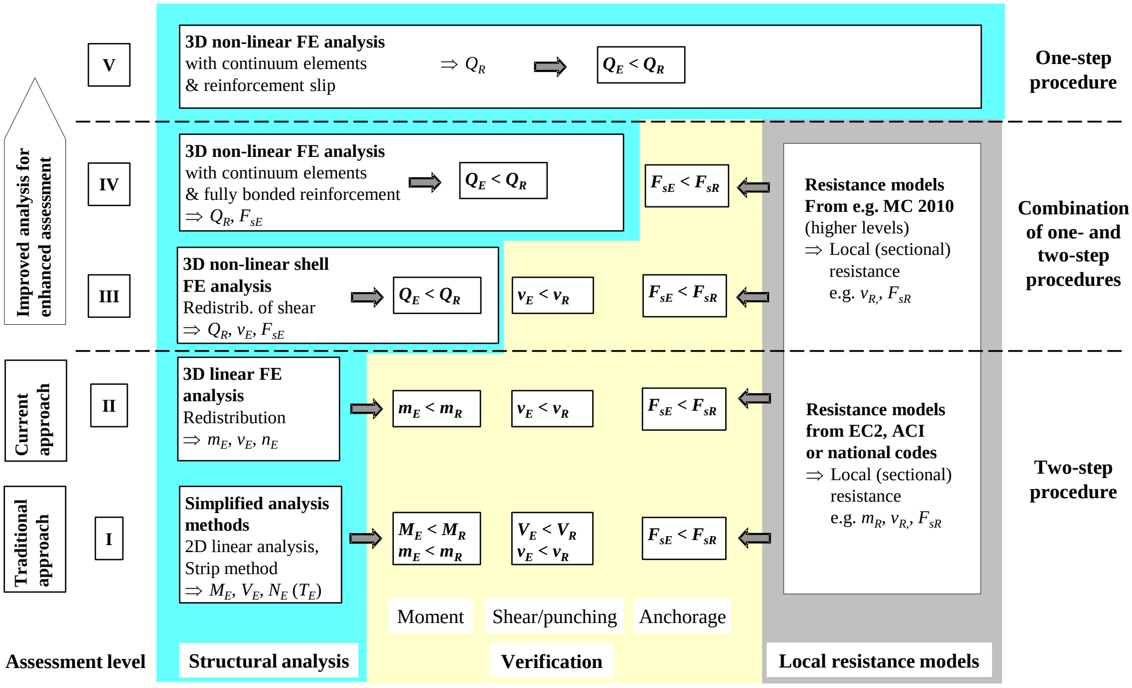

Figure 15 Scheme for multi-level assessment strategy of RC bridge deck slabs (Plos et al., 2017).

The multi-level assessment strategy was developed for assessments of load-carrying capacity with associated responses of RC slabs, but can be generalised for assessment of concrete bridges through the following levels and methods:

- Level I: Simplified methods are used (typically, code provisions or simplified mechanical models).
- Level II: The analysis is performed assuming linear elastic behaviour to be able to superimpose the effect of different loads, in order to achieve the maximum internal forces throughout the structure for all possible load combinations. The internal forces (axial forces, shear forces and flexural moments) are then compared to the corresponding resistances determined by local models for bending, shear, punching and anchorage of reinforcement.
- Level III: Non-linear FE analysis is used, with the capability of reflecting the flexural strength of RC beams and slabs directly in the FEA. However, at level III, the (out-of-plane) shear strength has to be determined using local resistance models.
- Level IV: Both bending and shear type failures, including punching of slabs and torsion of beams, can be reflected by performing the non-linear analysis using 3D continuum elements coupled with fully bonded reinforcement. For this reason, at level IV, bond strength and its effect to shear type failure has to be verified separately.
- Level V: It is a refinement of level IV, where the bond-slip behaviour of the interface between the reinforcement and the concrete is included. With this level of accuracy in the structural analysis, no failure modes need to be checked separately using resistance models. Thus, the load carrying capacity at the structural level V can be determined using a one-step procedure.

This method differs from the concept of level-of-approximation (Muttoni and Ruiz, 2012a, 2012b) in MC2010 (fib, 2013) in that MC2010 focuses on resistance models for different failure modes while this approach focuses on the structural analysis of the structure and connect the structural analysis on different levels with resistance models on different levels from Eurocode 2 (CEN, 2004) or MC2010 (fib, 2013). This multi-level assessment strategy can be seen as a complement to the concept of level-of-approximation approach in MC2010.

The highest levels of the multi-level assessment strategy easily result in extensively large models when assessing large and complicated structures like bridges. Consequently, they are still only realistic to use for critical load cases and in critical details of important bridges. Furthermore, the models need to be based on verified modelling methods since inappropriate modelling choices may lead to unrealistic results or overestimation of the capacity. Nevertheless, they can provide better understanding of the structural response and can thereby help to prove that the structural capacity is sufficient and that interventions can be postponed.

The multi-level assessment strategy described here, so far has been focusing on RC structures; however, the same principles apply for any kind of structural response model.

4.1.2 Load/exposure modelling

The most dominant variable load acting on a bridge is the traffic load from vehicles or trains. Such loads may be difficult to predict owing to a significant degree of variation in practice and over time; structural codes therefore use simplifications on the safe side for design purposes. Since the design load cases should cover many different bridge types and materials, it is likely that an existing bridge has a capacity for withstanding larger loads compared to the design situation; i.e. the degree of conservatism surrounding the design loads may be quite high. This extra capacity may be verified with more advanced analysis methods described in the previous chapter, or by measuring the actual loads acting on the structure as described in chapter 3.

Another option is to predict the loads acting on a specific bridge based on the traffic intensity using probabilistic modelling (Carlsson 2006). To be able to perform such modelling, the basic variables have to be represented by distributions where the most important variable is the traffic load. For design and evaluation purposes, it is the distribution of the heaviest vehicles that are of interest. The most suitable way of defining this is by the use of extreme value analysis of measured data (Coles 2001). To find a distribution best representing traffic loads, measurements of traffic on the same road section must be performed during several years and at multiple locations. This is not realistic and such data will likely never be available; traffic loads must therefore be modelled using simulations. For a background on this see e.g. Melchers and Beck (2018). Another possible approach is to use extrapolation to find the extremes using either classical extreme value techniques, see e.g. Nowak (1993), or the peak-over-threshold method, see e.g. Carlsson (2006) and James (2003) who have used this method to model road respectively railway traffic loads.

According to Carlsson (2006) there are three different approaches for modelling traffic loads on road bridges:

- Theoretical models of vehicles
- Extracting measured vehicles from a database and passing them over a bridge to calculate section forces
- Determining random variables describing a vehicle such as distance between axles, axle pressure and traffic composition

Apart from these choices, the traffic situation at the bridge site is of importance. The level of loading will be different depending on the traffic situation; e.g. a free flowing traffic will not give the same load effect as congested traffic or traffic that has stopped on the bridge. Other important factors affecting the section forces, i.e. the load effect, is vehicle position in the transverse direction, distance between consecutive vehicles, dynamic amplification and model uncertainties related to traffic loads.

As mentioned earlier, Carlsson (2006) studied the possibilities for modelling traffic loads on bridges using the peak-over-threshold (POT) method. As a basis for the modelling, B-WIM measurements in 15 different locations in Sweden during 2 years were used; resulting in a total of 280000 vehicles measured. Of these vehicles, approximately 31000 were heavy vehicles (>3.5 tons) which were included in the modelling and simulations.

The focus of the study was to evaluate how statistical extreme values of load effects could be determined using the traffic intensity as input. Different bridge types and traffic situations such as a single heavy vehicle or congested traffic were studied, with the final results being compared with load effects obtained by using design values from the design code valid at the time.

The results showed that the traffic intensity and the characteristic load values obtained by the POT-analysis are highly dependent, in which an increasing traffic load results from higher traffic intensity (i.e. heavy vehicles per day). It was also shown that the load effect obtained from using load values found in deign codes were 1,45-1,75 times larger than the load effects obtained from simulations based on the measured vehicles, even though heavier vehicles than allowable by law were measured. This shows that the actual load situation on a bridge may be different compared to the (conservative) design situation, and that obtaining load and load effect values related to the actual situation for a specific bridge may lead to possibilities of using a bridge more efficiently. If an initial calculation shows insufficient capacity, it may be possible to show that the capacity is in fact sufficient if the actual load values differ from the design loads.

The methodology from Carlsson (2006) along with B-WIM approaches and measurements of transverse vehicle position have also been used to verify the traffic load situation and the safety level of the Öland bridge in Sweden (Carlsson and Karoumi 2008). The owner of the bridge wanted to increase the allowed bogie load with 2 tons, and the initial deterministic analysis showed that a section of the bridge had insufficient capacity for this increase.

The results presented by Carlsson and Karoumi (2008) determined that the bridge had sufficient capacity and safety level when measured data and probabilistic load models were used. This gave the bridge owner the possibility to increase the allowed traffic load and save large sums of money that was going to be used for strengthening. This shows the possibility of using more advanced load modelling techniques and the importance of obtaining knowledge of the actual traffic situations.

Other variable loads may also be of interest such as temperature or wind, where modelling techniques also are available. Larsson (2012) studied the effects on temperature in concrete bridges, and showed the possibility of using climatic factors such as solar radiation, air temperature and wind speed as input data for obtaining temperature loads. For wind loads, the aerodynamic effects on bridge superstructures and towers are of particular interest, which may be studied by computer fluid dynamics (CFD) (Xu and Zhang 2017), wind tunnel tests (Diana et al 2013) or a combination of these methods (Yang et al 2017).

4.1.3 Risks and uncertainties

If there were perfect knowledge of a structure, its components and connections, as well as the internal and external exposures over time – the condition of a structure might be assessed without need for inspection or monitoring actions. Unfortunately, the world is not deterministic and there are a number of often time-dependent uncertainties which need to be considered to confidently determine a suitably accurate assessment of structural performance; these include uncertainties related to material properties, environmental exposures, mechanical loading, operational conditions, model uncertainties, etc. It is critical that these uncertainties are given due consideration in order to make informed decisions regarding suitable performance assessment procedures for existing bridges; especially in light of the relatively high costs associated with the repair and rehabilitation of existing structures.

In general, the uncertainties influencing structural performance are often classified into two fundamental types:

1) Aleatory variability – an object quality relating to inherent natural variability, and

2) Epistemic uncertainty – a subject quality related to (a lack of) knowledge (or data).

This distinction is convenient in an engineering analysis, since epistemic uncertainties can be represented in the model by introducing auxiliary non-physical variables (Kiureghian and Ditlevsen, 2009). A third type of uncertainty, *ontological uncertainty*, arising from the unknown and unexpected has also been mentioned in the literature. While aleatory and epistemic uncertainties can be explicitly considered using stochastic modelling, probabilistic methods may be ill-suited for dealing with these ontological uncertainties and other indirect methods may be more appropriate; e.g., quality assurance or pro-active safety management schemes (Elms, 2004).

An important distinction can be made between the management of existing structures and the design of new structures. The prior allows for a direct reduction of epistemic uncertainties through utilization of available or collected data pertaining to the state of the structure as it *actually is*. The design of new structures is guided by established and codified design approaches which are calibrated using reliability-based safety formats in an effort to reduce the likelihood of structural failures, loss of serviceability, etc. These calibrations are based on uncertainties for a population of structures and may be overly conservative for the assessment and management of an existing structure. The aforementioned reduction of epistemic uncertainties is thus an integral part of the process of managing a degrading bridge stock as it provides more representative data concerning the state of an existing bridge. This data can be used to update the modelling assumptions, adjust assumed material and/or strength parameters as well as the circumstances to which the bridge has been, and will be exposed to in the future. It is important to highlight this last point; i.e. that considerations of uncertainties is not limited to those factors which determine the capacity of the structures but also to the demand placed on the structure (e.g. loads). Thus, while monitoring, on and off-site measurements, inspections, etc. help with reducing the uncertainties related to a bridges capacity/performance, similar approaches can be employed for determining the uncertainties related to the demand placed on the structures. Examples include B-WIM measurements to determine the distribution of axle-loading for a road bridges or the measurements of varying climactic factors which determine temperature and moisture effects.

Thus, generally speaking, if the statistical basis of the assessment of the uncertainties is limited, then “statistical” epistemic uncertainties might play an important role. The auxiliary variables capture information obtained through gathering more data (or, if there is adequate information, the use of more advanced scientific principles), which is an important aspect for inspection and monitoring. Another important aspect is that these variables define statistical dependencies (correlations), which arise among different components that have common uncertainties, in a clear and transparent way. Probabilistic description of uncertainties may be presented in the form of random variables, stochastic processes and/or random fields depending on the case and available information. With the probabilistic model, temporal and spatial dependencies might be taken into account.

Hazards are events or a set of events with a potential for undesirable consequences (JCSS, 2008). These events can be endogenous and exogenous effects on the system constituents. A probabilistic characterization of the systems exposure to a hazard requires a joint probabilistic model for all relevant effects relative to time and space. The characteristics of exposures might be quite different, depending on the individual exposure types. Some of them happen suddenly (e.g., technical failures or accidents) while others evolve much slower (e.g., snow accumulation or deterioration). Some exposures, on the other hand, might have a specific pattern over time and space (e.g., human error). It is important to recognise these differences while characterizing exposures.

In the context of inspection and monitoring quite often the joint representation of several exposures is required; e.g., the joint occurrences of live loads, dead loads and environmental loads together with chloride induced deterioration can constitute an important scenario for the assessment of the risks for a reinforced concrete road bridge. Realizing the risks associated with the hazard scenarios associated with these types of exposures requires dues consideration for the underlying uncertainties involved; both in relation to the relevant exposures as well as the pertinent deterioration processes. Deterioration processes acting on structures are highly uncertain, since their underlying processes are rarely fully understood and/or influenced by several parameters that are difficult to control. Due to this uncertainty the likelihood of failure of components and thus that of the entire system will increase in time if no maintenance or inspection actions are performed. The probabilistic models for deterioration processes are usually based on a mixture of physical understanding, observations and experience. Observations on actual deterioration levels (obtained by inspection or monitoring) therefore can reduce the (epistemic) uncertainties surrounding the predictions about structural performance. The degree of consideration for uncertainties related to these predictions in practice, whether explicit or implicit, is unclear and may depend on the type of condition assessment being made and the approaches employed by those involved.

It should be kept in mind that the inspection and maintenance actions themselves are subject to significant uncertainties. The quality of inspections is usually described in terms of their ability to detect and quantify the type and magnitude of defects or damages to the structure being inspected. Thus, different inspection methods and techniques may be more or less useful for the identification and characterization of different deterioration processes; insofar as it relates to the quality of the information which is obtained.

Repair and failure events of system components may have significant consequences on safety and economy. Inspections, repairs and failures have immediate consequences on direct financial costs; the event of failure may in addition have consequences on the potential loss of lives as well as economic consequences related to disturbances in the transport network. The assessment of the economic consequences related to an inspection plan including costs of material damage and costs of production and operational loss can be assessed e.g. using decision/event trees. Extending the uncertainty assessment to include consequences provides a context from which rational decisions can be made. This extension results in a risk based (or risk informed) approach of which there are numerous methodologies; both qualitative as well as quantitative.

In a risk-informed approach, the system model should be based on scenario representations (Figure 16) of the different possible sequences of events which might affect system functionality (or performance), taking into account their likelihood of occurrence as well as their consequences (JCSS, 2008).To be able to assess generic risk indicators of a system it is often convenient to distinguish between direct and indirect consequences. Direct consequences are associated with damages or failures of the system constituents; whereas indirect consequences are associated with the loss of the functionalities of the system (and by any specific characteristic of the joint state to the constituents and the direct consequences themselves).

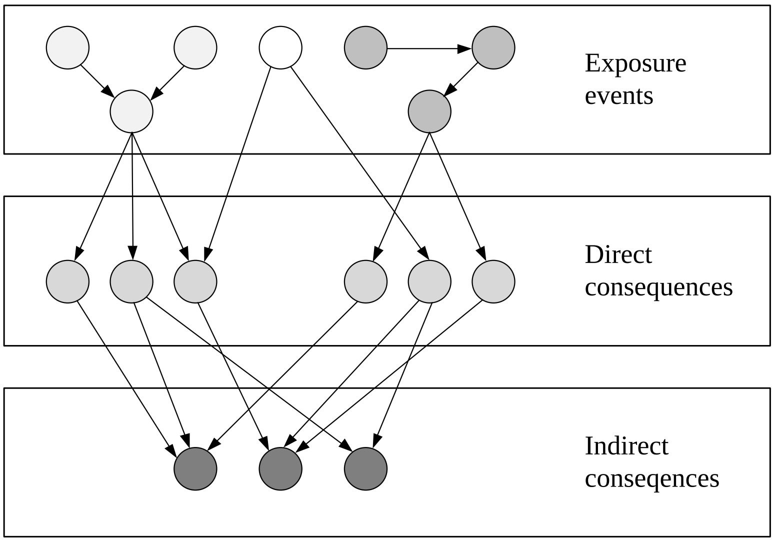

Figure 16 Scenario based representation of consequences (JCSS, 2008).

Direct consequences can be expressed in forms of e.g. number of injuries, loss of life, economic losses, impact on the environment, or simply alterations in the system characteristics. Indirect consequences are usually expressed as e.g. the aggregation of economic losses caused by constituent failures or the degree of degradation of system functionality as the effect of the failure of single or multiple system constituents. It should be noted that indirect consequences can often be more extensive than direct consequences, thus their modelling in an appropriate way is essential and has a great influence on the total risks and thus on engineering decisions. Models for determining direct consequences related to local damage as well as the indirect consequences (including human casualties and traffic disruptions) related to follow-up failures of bridges can be found in the literature (e.g., Björnsson 2017, Maibach et al. 2008, Wong et al. 2005).

In light of the aforementioned modelling possibilities, there are three main levels for consideration of uncertainties, as shown in Table 4. The main difference is related to the extent of probabilistic information used in the model. In relation to condition assessment of bridges, different levels may be appropriate at different stages of assessment procedure.

Table 4 Levels of uncertainty considerations.

Level	Description	Indicators/criteria
1	Deterministic	Utilisation based on code compliance
2	Reliability based	Reliability index, probability of failure/outcrossing, first passage time
3	Risk-based	Vulnerability, robustness, risk acceptance (e.g. ALARP, F-N curves, etc.)

The first level involves deterministic calculations in which case representative values for the variables involved are used and the results compared with prescribed criteria; i.e. in the form of code specified safety targets.

The second level includes reliability-based approach to estimate the probability of exceeding certain limits states. This might involve certain approximate iterative calculation procedures or full probabilistic description of the joint occurrence of the random variables to estimate failure probabilities. Thus, even within reliability-based methods there is a great variety of possible idealisations and subcategories could be defined. Usually those parameters which are considered most significant are modeled as random variables, with associated distribution parameters, while the remaining variables are considered deterministic.

At the third level the consequences of failure are considered explicitly in the analysis. This level of modelling is commonly used for bridges, of which disruption of the services would lead to major economic consequences.

Similarly to structural modelling the use of higher level models might be difficult to justify for many practical cases. Moreover, the confidence in relying on more complex models might be questionable if the information provided to the model is not sufficient in terms of quality and quantity.

4.2 Decision making

4.2.1 Engineering decision making

One of the most powerful aspects of inspection and monitoring techniques concerning civil engineering structures is that the information provided by them can be utilized to reduce uncertainties concerning decisions about the structure. However, this additional information has a price which might or might not be in balance with the benefits gained by the reduced uncertainties and thus risks. Unfortunately, in practice, the effectiveness of inspection and monitoring becomes known after it has been carried out/implemented. However, this problem could be overcome by the application of Bayesian decision analysis.

As described by Ditlevsen and Madsen (1996) engineering decision making can be interpreted as playing a game where the decisions by the decision maker aim to optimize the expected utility according the decision maker's preferences and can be analysed by the game theory from von Neumann, J. and O. Morgenstern (1944). To "win" the game the rules must be clear. Figure 17 illustrates constituents of the decision problem/system which can be seen as the equivalent to the constituents, i.e. the rules of a game.

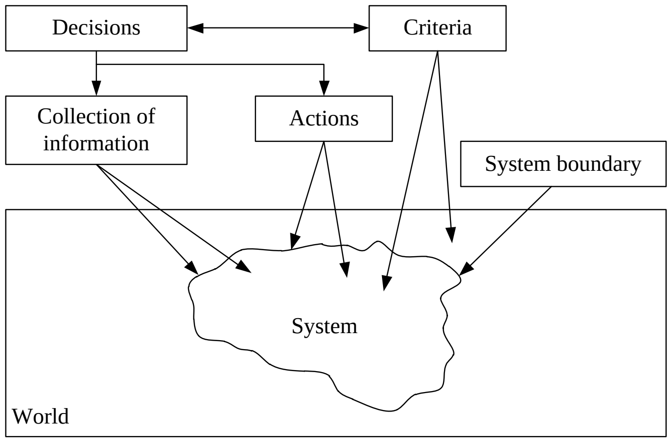

Figure 17 Main constituents in risk-based decision analysis (Maes and Faber, 2008).

As described by Faber and Maes (2005) this means, that information is needed about the assets, its surrounding, the possible consequences of actions, the interrelation of different factors that affect system performance etc. Participating in the game is then carried out by "buying" physical changes in the system or "buying" knowledge about the system such that the outcome of the game should be optimized.

In the process of quantifying the value of inspection and monitoring and thus to decide whether they should be undertaken or not, uncertainty of the occurrence of future exposures/hazards, the system behaviour, system components etc. should be accounted for. To be able to deal with these uncertainties in a consistent and rational manner a clear definition of several constituents of the decision problem is needed concerning: the system, the rationale of decision ranking, perception of risks and consequences (Faber and Maes, 2005).

A generic framework and principles for risk-based engineering decision making is given by the Joint Committee on Structural Safety (JCSS) (JCSS, 2008) and adopted in the recently revised ISO 2394 (ISO, 2015). In this framework the traditional concept of risk is widened and includes the aspects of the benefits achieved from the decisions. Thus, risks can be related to the concept of utility from the statistical decision theory (Raiffa and Schlaifer, 1961). The framework enables:

- The ranking of decision alternatives which is consistent with available knowledge about the system;
- Updating of risks according to knowledge which may be available in the future;
- Responsive decision making in the future in dependence of knowledge available then.

A risk-based (or risk-informed) approach is the highest level among probabilistic approaches concerning evaluation of structural performance and making decisions about structures. However, it is also the most complex one and needs the largest effort with regard to modelling, input and analysis. The modelling of consequences might be extremely cumbersome.

When thinking about model updating an obvious advantage of the risk-based approach is that it allows the application of the pre-posterior decision analysis, i.e. decisions based on "unknown" information. Based on the difference between pre-posterior and prior-analysis the value of information (VoI) can be assessed, which facilitates an optimal allocation of available (monetary) resources. For this reason, this approach is used e.g. in the off-shore industry, where inspections are highly expensive.

The risk-based approach can be seen as an optimisation problem, where among the feasible decision alternatives (i.e. those that have a positive benefit) the one with the maximum benefit should be selected. The acceptance criteria related to e.g. life safety or the environment can be interpreted as constraints to the optimization problem. It means that in practice the optimal decision is not always acceptable, thus a sub-optimal solution needs to be selected.

When assessing risks, it is important that all anticipated future consequences should be accounted for including both the consequences which are associated with uncertainty and the consequences which are (deterministically) related to decisions e.g. future costs of maintenance actions.

4.2.2 Group decisions

A risk-based decision making approach is an excellent tool to facilitate the decision making process and to prioritize the course of actions that needs to be taken in order to achieve the benefits of functioning of bridges. However, quantification of risks can be a challenging task, especially if several people are involved with different preferences. Various methods exist to overcome these issues and to facilitate group decisions in a rational way. Some of them, which could be used for bridge maintenance, are summarised in the followings.

Fuzzy group decision making: In order to accomplish an effective risk-based framework, a fuzzy group decision making (FGDM) can be employed (Wang and Elhag, 2007). When precise definitions or boundaries do not exist or are too rigid the concept of fuzzy logic is very useful. The FGDM method is based on linguistic terms to define risk factors. Due to the difficulty to provide precise numerical values for likelihood and consequences of an event, the fuzzy approach is not only a flexible and effective modelling, but it also enables the decision process.

The first step is to define the inputs and outputs that are evaluated in the process. This task is performed in parallel with the assessment phases (inspection and monitoring) to guarantee compliance with the process.

Once this first step is ready, a mapping between critical inputs and its association with membership functions is defined. Each input is associated to the fuzzy inference system, setting the right attributes and ranges. The membership functions are described as functions of likelihood and consequence ratings. Both likelihood and consequence rates are assessed in agreement to a hierarchical structure according to experts in the area. The experts employ a terminology for decision analysis instead of quantifying it numerically.

The outcome in the current context is characterized as the value for the decision-making process. The maintenance process of structures needs an action course. This action course is planned according to the complexity of the structure and the environment variables involved in the process. The complexity and relevance of these variables will directly influence the exact assessment, i.e., the final decision on whether an intervention is needed or not.

Expert elicitation: if no or little data are available, experts' judgement can be directly utilised to support decision making. Expert's judgment, in the form of subjective probability distributions, can be a valuable addition to other forms of evidence in support of decision making. However, according to Morgan (2014) expert elicitation should be undertaken only when other methods are proven insufficient to support timely informed decision making.

A main challenge in any elicitation is how to combine the experts' opinions. In general, for a complex and uncertain problem if single experts are asked to provide their judgment around the expected value of a variable and to quantify their uncertainty, they typically provide an unreliable estimate of the mean accompanied by a small uncertainty (Cooke, 1991). By contrast, if a large group of experts is elicited and their opinions are weighted equally, a good estimate of the mean of the variable is typically obtained, but the associated uncertainty is typically very wide.

Cooke's model (Cooke, 1991) offers a rational means of quantifying the uncertainty by an optimized weighting of experts according to their demonstrated ability to quantify uncertainty around particular relevant variables. Generally, however not always, this produces an outcome distribution with formally quantified uncertainty that falls somewhere between the two extremes.

Delphi Method: the method is a structured group communication characterised by anonymity of respondents from a panel of experts, controlled feedback with a statistical description of responses, and multiple iterations to reach a consensus. Using the method, the most unbiased and reliable result can be obtained (Dalkey and Helmer, 1963).

5 Current Swedish practice

As mentioned earlier Trafikverket uses their own system, called BaTMan, to manage their stock of bridges (and tunnels). They collect and store various data about the bridges required to make decision about their maintenance at operational, tactical and strategic levels (Hallberg and Racutanu, 2007).

The management data in BaTMan includes administrative data, photos, technical data of the object, load capacity data, and all inspection records. For some objects, construction drawings can also be found. A specification of the data Trafikverket demands can be found in Trafikverket (2014). Requirements and advises on the performance and documentation of inspections can be found in the online manual Trafikverket (2015). These documents ensure that the activities (e.g. inspection) related to the management of bridges are carried out consistently and properly. Also, the inspection manual provides information on typical damages and their causes for the common bridge types and their structural members.

Based on the bridge inspection the physical and functional condition of both the structural elements and the entire bridge is determined and a condition class (CC) is assigned by the bridge inspector. The CC spans from 0 to 3 (see Table 5) and describes to what extent structural members fulfil the functional requirements at the time of inspection.

Table 5 Condition classes (CC) system used in BaTMan.

CC	Assessment	Follow-up
3	Defective function	Immediate action is needed
2	Defective function expected within 3 yrs	Action is needed within 3 yrs
1	Defective function expected within 10 yrs	Action is needed within 10 yrs
0	Defective function expected beyond 10 yrs	No action is needed within 10 yrs

An assessment of existing structures may be necessary when the reliability of a structure is questioned, alterations to the structural system are needed, or by requirements from authorities. This assessment can be performed by applying the same rules as for design of new structures. This will, however, in many cases show insufficient reliability. As pointed out in Vrouwenvelder and Scholten (2010), the safety assessment of an existing structure differs from that of a new one in several aspects. The main differences are:

- Increasing the safety level is usually more costly for an existing structure than during the design phase of a new.
- The remaining lifetime of an existing structure is typically less than the expected lifetime of new structures, thus the exceedance probability of certain load levels might be different.
- For an existing structure, inspections and measurements may be used to reduce uncertainties.

For the listed reasons the reliability levels may be reduced for existing structures. To handle this, the Swedish Transport Administration has issued a regulation intended for assessment of existing bridges (Trafikverket, 2016). The methods suggested, and the partial safety factors stated indicates lower safety margins than adopted in the Eurocode for new structures.

The parts related to inspection and monitoring in the Swedish regulation for assessment of existing bridges (Trafikverket, 2016) are briefly summarized below.

- The regulation supports destructive sample testing for material properties of concrete, steel and aluminium. Methods are prescribed for evaluation of characteristic values. For some structures as, e.g. unreinforced concrete, material testing must be performed. For steel bridges build before 1970 the chemical composition must be determined to evaluate the material toughness.
- Testing of geotechnical properties is supported. It should be noted though, that assessments are often limited to the superstructure.
- Dimensions related to loads such as the thickness of the paving, can be measured rendering a reduction of the partial safety factor for that load.
- Fatigue assessment based on measured response is supported. Strain measurements are prescribed and a minimum duration of one week is recommended.

The verifications build on a deterministic (semi-probabilistic) format using partial safety factors.

Reliability-based assessments are allowed but not supported by any guidance. Therefore, internationally recognised documents for the probabilistic assessment of existing structures might be applied, such as ISO 2394 General principles on reliability of structures (ISO, 2015) and ISO 13822 Bases for design of structures – Assessment of existing structures (ISO, 2010). More practical guidance is available from JCSS (JCSS, 2001 and 2008).

6 Conclusions

In high-consequence industries, such as nuclear, off-shore and oil and gas, modern maintenance approaches have already passed the 3rd generation of maintenance and utilise modern technologies and risk-based methodologies for decision making. Modern inspection and monitoring technologies in the condition assessment of major bridges are already in use and their application is increasing.

It is expected that modern approaches and the utilization of information for decision making concerning structural integrity management will be used more and more in the future for the maintenance of bridges as well.

Project BIG BRO aims to explore these possibilities and provide a framework for a consistent and rational way of making decisions about condition assessment of bridges with maximising the expected benefits provided throughout their entire lifetime.

This is in theory possible with the use of pre-posterior decision analysis, which takes into account the various types of uncertainties during the decision-making process. However, it typically requires significant efforts concerning statistical modelling and computation. This is a major obstacle for practical application for managing a large bridge stock.

A main challenge for the project thus is to provide a framework which is consistent with the general theoretical concept, but simple enough for practical purposes and particularly suited for bridge management.

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