DATA-INFORMED SAFETY ASSESSMENT OF CONCRETE STRUCTURES

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Keywords: bridges, monitoring, structural diagnostics, data-informed safety assessment, reliability, damage processes

The safety assessment of existing structures is triggered by doubts regarding the actual safety, which may arise from e.g. the observation of deterioration or damage during inspections, reaching of the end of the design lifetime or unforeseen increase of actions on the structures. The safety assessment of existing concrete structures differs from the design of new structures in several aspects. The first one is the choice of the target reliability levels for the assessment and the treatment of safety requirements in semi-probabilistic verifications (e.g. setting partial safety factors for existing structures). The second one is the availability and adequacy of performance analysis models for existing structures: those given in the code for the design of new structures may no longer be valid and serve as an implicit proof of compliance for existing structures (e.g. in case of deterioration, where the limit states should be re-formulated in order to include information on the suspected damage or deterioration mechanisms, task which is particularly challenging since they generally vary in space and time). The third aspect is related to the availability and use of structure-specific information: inspections, tests and monitoring may be performed to assess the structural condition, the action effect and/or the actions on structures and enable improvement of the structural assessment. In this respect, the structural engineers are faced with not always straight-forward choice of (i) the type of information needed for the assessment, (ii) the required amount of information, (iii) the location(s) where the information should be retrieved and (iv) the procedures for sound use of information in verifications. This contribution discusses the approaches to data-informed safety assessment, reflecting on the four aspects mentioned above and making distinction in the use of direct and indirect structure specific information. The contribution is outlining the vision and approach developed in the currently ongoing H2020 CSA IM-SAFE EU-project, which aims to support the preparation of the mandate for CEN for further amendment to the existing EU standards enabling data-informed safety assessment taking into account inspections, monitoring and testing.

ASSESSMENT METHODS FOR NEW AND EXISTING STRUCTURES

Malfunction or, to its extreme extent, collapse of infrastructure assets can cause huge negative impacts and long-term drawbacks on the economy and society [1]. Regrettably, in the recent years, safety risks to transport infrastructure have become critical and manifested in major disasters, frequently attributed to the structural failures due to maintenance deficiencies. Bridges and tunnels, which are critical elements of the transport infrastructure networks, have in constantly increasing number of cases reached their design service life and are subject to ageing and progressive deterioration processes. The limit states assessment methods should be re-evaluated and, in needed, re-formulated in order to take into account the suspected damage or deterioration mechanisms. This is particularly challenging when it comes to consider the effect of damage or deterioration which may vary in space and time, as this would possibly necessitate an explicit representation of the complex system interactions in the structure. Moreover, most bridges currently carry a traffic composition, both in terms of traffic volume and intensity, more onerous than what they were originally designed for. Besides, the continuous evolution of modern technologies has a deep effect on mobility and consequently on the actions that depend on it: automotive driving, alternative fuels and electrical vehicles are few examples of the latest technologies which are becoming extremely widespread and directly affect the traffic loads (e.g. effect of platooning) or hazards in general (e.g. different fire action due to alternative fuels) [2]. Climate change has also a significant effect on the loads and exposure conditions for structures (e.g. extreme wind, snow, temperature, precipitation,..) relevant for design of a new structure or assessment of an existing one [3]. As such, the need for a better knowledge and understanding of uncertainties, risk acceptance and risk differentiation for both new and existing structures has led recognizing the advantage of taking in to consideration the additional information that can be acquired by inspection, testing and monitoring in case of existing structures. In this context, the H2020 CSA IM-SAFE project has been initiated to support the European commission and the European committee for standardization (CEN) in preparing new standards enabling the use of inspection, testing and monitoring for data-informed performance assessment of existing transport infrastructures and optimal maintenance decision-making based on timely available, accurate and relevant information. The present paper illustrates the main findings of the project development regarding data-informed safety assessment of concrete structures [4].

Structural Performance assessment

The structural performance of a system or a component refers to the behaviour, or a condition as a consequence of actions, usually classified by means of a quantitative parameter (referred to as Performance Indicator - PIs) related to safety, serviceability, durability, or robustness [5,6]. Structural performance might refer to the absence of adverse states that compromise the intended purpose of the structure. Structural failure of a component or the entire structure are obvious examples of such adverse states; excessive deflection, deformation or vibration are others. In order to assess the performance, one shall select a set of PIs that can be defined on various levels of abstraction, such as structural characteristics (e.g. stiffness/flexibility, load bearing capacity), response parameters (e.g. internal forces, stresses, deflections, accelerations, crack sizes), utilization factors or functionalities (e.g. safety for people, energy consumption, robustness, usability, availability, failure probabilities). Appropriate models shall be set up to establish the relation between the various levels of abstraction. In case of data-informed approach, and adequate inspection, testing monitoring systems and survey techniques are to be identified to provide the necessary data to quantify the PIs used in the verification process. The structural performance of an existing structure is to be assessed by a set of activities undertaken to verify the reliability of an existing structure, allowing a prognosis to be made of current and future response, taking account of relevant deterioration mechanisms and, if appropriate, predictions of potential future damage. The levels of the verification used to assess the compliance with the requirements for all design/assessment situations and commonly recognized are: the risk level, the probabilistic reliability level, and the semi-probabilistic level (Figure 1).

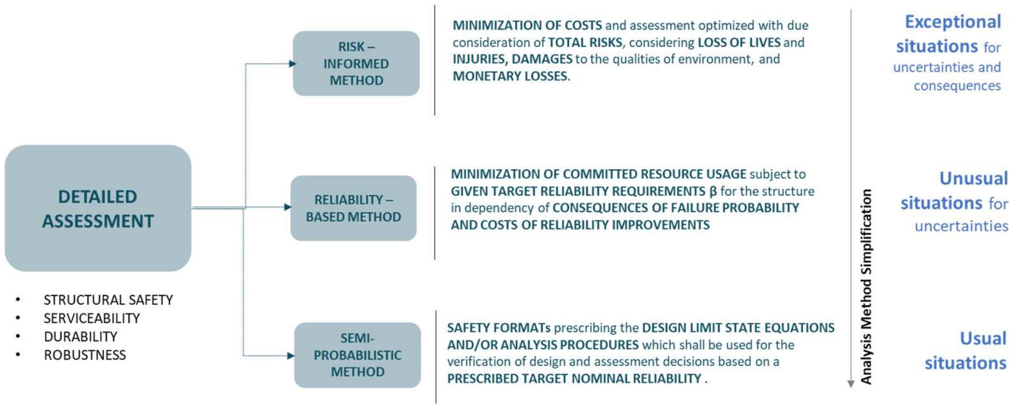


Figure 1 – Structural Performance Assessment method.

It is to be highlighted that, similarly to the design of new structures, whatever method is selected, the assessment of existing structures can be carried out with different levels of approximation, based on the degree of accuracy required to fully describe the structural response. In the Level of Approximation Approach (LoAA), in fact, a series of parameters and a set of design equations are used to characterize the behaviour of structures. Anyhow, all analyses performed are approximations of reality with different levels of accuracy. The levels of accuracy of the assessment can also be enhanced by the integration of the as-design information with the acquired data coming from inspection, testing, and monitoring.

Difference between new and existing structures

When approaching the verification of existing infrastructures, it becomes crucial to identify and correctly represent the difference between new and existing conditions, with due attention to the parameters that mostly influence the assessment and its boundary conditions. Figure 2 explores some of the peculiarities to be accounted for when dealing with existing structures.

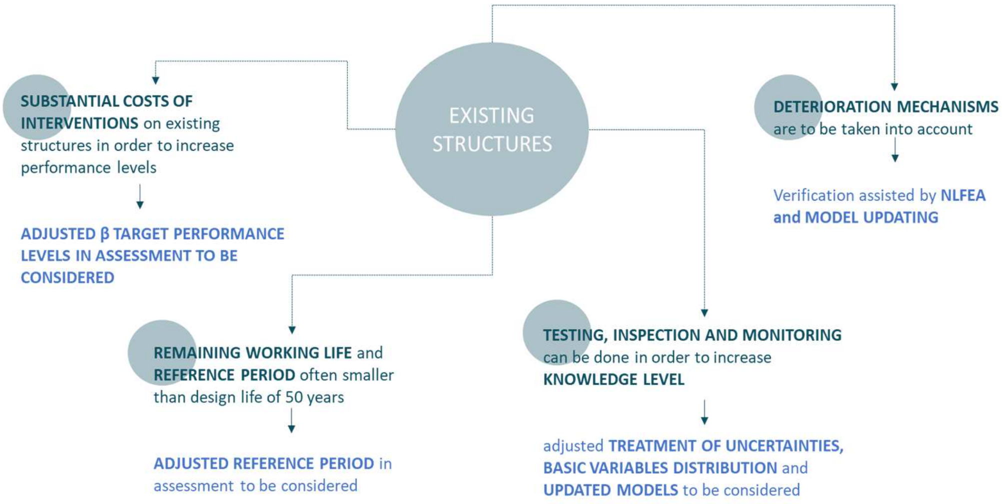


Figure 2 – Key peculiarities of the existing structures.

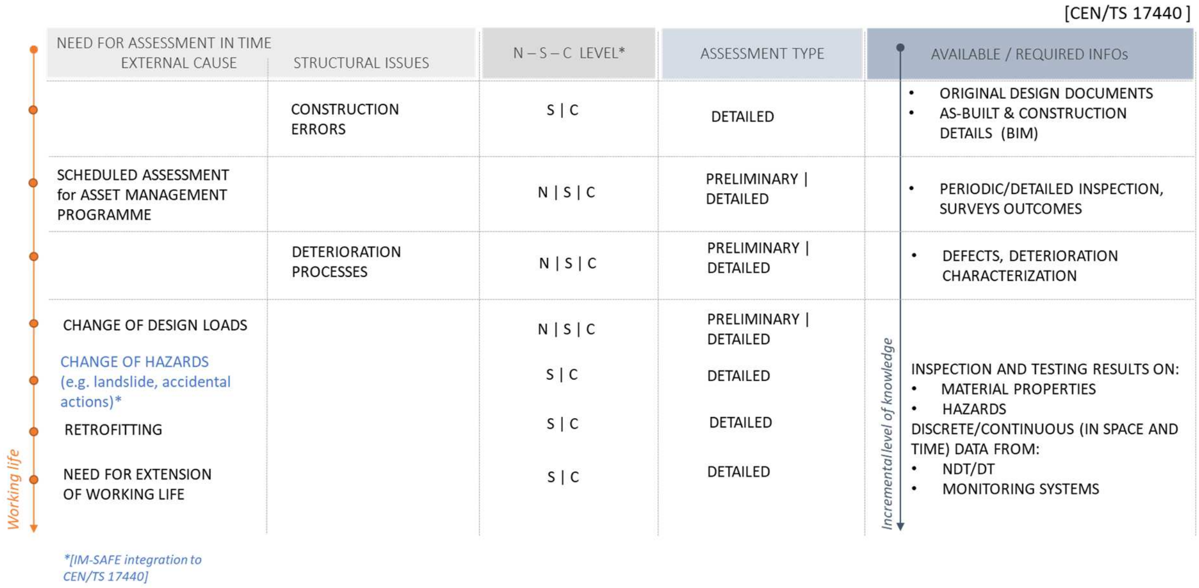
Firstly, it is not to be discarded that existing structures often have a remaining working life smaller than design life of 50 years. Substantial costs are to be faced when planning interventions on existing structures in order to increase the performance level up to the one expected for new structures. A conservative design does not usually lead to a significant increase in structural cost, while a conservative assessment can result in unnecessary and costly repairs or replacement. Based on the above, the aim of the future standardization for existing structures is to consider adjusted target performance levels, adjusted reference period as well as adjusted treatment of uncertainties in the assessment. This is recognised both in the fib Model Code 2020 [7] and in IM-SAFE project results [4]. Specification of target reliability levels is one of the key issues of the assessment of existing structures [14]. Optimal target reliability levels are to be derived for existing structural members considering economic and societal aspects, recognising that the requirement to reach the same target reliability levels for existing and new structures is uneconomical. In case of existing structures, the acceptance of the actual state, the upgrade of an existing structure is the possible scenario to follow if the structure is to be kept in use. In the context of aging structures, the so-called condition limit states may be considered to describe adverse states that have the potential to lead to critical states for the structural integrity (such critical states often relate to tolerance to material deterioration or partial damage of structural elements). In the case of assessment of existing structures with respect to durability on the basis of full-probabilistic methods, the same target reliability level for condition limit state associated to durability can be applied as for new structures, unless ULS and/or SLS verifications or the application of risk-based methods justify a different β level. Alternative values for target reliability levels of condition limit states compared to new structures may be considered applicable when accounting for e.g. altered service life, altered requirements on structural behaviour over the remaining service life (i.e. cracking, spalling,...) and the actual progress of the deterioration. Thus, two reliability levels are needed: β_0, which is the minimum level below which the structure is unreliable and should be upgraded, and β_{up}, which is the target level indicating an optimum upgrade strategy. Concerning new structures, instead, β_{new} is defined as the level indicating desired reliability for design of new structures. Hence, three levels of target reliability are differentiated and need to be established using economic optimisation and the marginal life-saving costs principle, taking into account the costs of safety measures and the failure consequence [4, 7]. Moreover, when assessing existing structures, one of the major challenges is how to deal with degradation phenomena and its impact on structural resistance and load effect in time. In this respect, in [4, 7] it is proposed to introduce an improved approach to the assessment of "actual" capacity. The format for specifying target reliabilities on an annual basis should be interpreted as a minimum requirement for each individual year during the design or remaining working life of the structure. Accordingly, it is recommended to consider in the performance-based assessment of the remaining service life the annual target reliability values, in the ultimate limit state or serviceability limit state verifications. Such verifications take basis in a coupled modelling of the damage initiation and propagation phases and, consequently, the present condition assessment model should consider the uncertainties typically considered in structural reliability calculations for ULS/SLS (as done for non-degrading structures) as well as those related to the degradation modelling. When assessing the structural performance and condition of existing structures by data-informed approach, the analysis has to be based on available information and on data gathered from testing, inspection and monitoring. These data can contribute to the creation of adequate structural models for existing (e.g. deteriorated) structures, given also the substantial costs of interventions in order to increase performance levels.

Deterioration mechanisms in existing structures

As described in [7,8], structures are inevitably subject to deterioration that progresses over time, so the real duration of the period of use of a construction is beyond the scope of design forecasts. In data-informed approach, the level of degradation is determined using models built from information obtained from inspection and monitoring activities, design data, previous maintenance work and environmental conditions. Corrosion, time-dependent deformations and the interaction with the environment are just some of the principal causes of loss of structural safety. According to [4, 7], it is of crucial importance to evaluate the aggressivity of the environment in order to identify the possible deterioration processes, calculate the threshold values for deterioration and the expected rate of deterioration and conduct preventive measures to avoid or minimize deterioration and its effects. Moreover, it is highlighted that, in damaged structures, deterioration may lead to loss of stiffness and a reduction of structural safety, so the bearing resistance of the structure and its structural members has to be assessed in order to determine the loss of load-bearing capacity due to cracking or swelling, the reduced cross-section of the concrete due to delamination and spalling, the reduced cross-sectional area and ductility of the reinforcement and, where possible, estimate the residual concrete/steel bond. The diagnosis process, executed on the basis on monitoring data, should reveal whether the structure suffers from any type of deterioration and determine which state the deterioration has reached. It is to be highlighted that deterioration models are characterized by a number of parameters which are hard to determine and that should be properly calibrated based on site measurements. The standardization process should provide a strong basis for the determination of accurate damage models and the evaluation of the degradation process in time, so that the consequences of the damage evolution in space and time could be included in the performance assessment considerations.

TYPE OF INFORMATION NEEDED FOR ASSESSMENT

As per most of the standards analysed [5,9,10], updating information of properties and performance modelling of a structure is an essential part of the assessment of existing structures. In assessment, an existing structure can be inspected, tested and/or monitored so that load, resistance, environmental parameters and global static and dynamic response can be measured on-site. As shown in Figure 3, the need for assessment, its type (preliminary or detailed) and its level of application (network, system or component) may be originated by different causes (external actions, damages, planned assessment) and could be based on various available information. The type of information needed may be very different, starting from the original design drawings, as-built and construction details, periodic investigation outcomes, and comprising additional information such as detailed survey campaigns, inspection and testing results on both the action and resistance sides, data acquisition from continuous monitoring aiming to characterize the structural response through PIs used for the performance verification (see Figure 3). In this context it is worth noting that has been demonstrated that the use of data obtained from monitoring systems could be crucial for the updating of the values to be used in both design and assessment of structures [2, 17]. The collection of data can be used to update prior information based on both direct and indirect information. Direct information is related to the basic variables that can be measured using a device or a survey technique, for which it is possible to update the probability distributions, mean values or assessment values (resistance, actions, degradation process evolution in time,..). Indirect information is related to the measurement of some indicators of the quantity of interest; for example, the probability of structural failure could be indirectly updated by using information from load testing or based on the past performance, or model updating methods, both deterministic or probabilistic, could be performed based on the measured indicators of the structural response (e.g. frequencies, dynamic response, deflections, rotations, etc.). Moreover, a differentiation of information could be established between so-called equality type and inequality type information. Equality type information is corresponding to measured variables and inequality type information denotes the information carried with a measurement that some variable is greater than or less than some predefined limit.


[CEN/TS 17440]

NEED FOR ASSESSMENT IN TIME		N – S – C LEVEL*	ASSESSMENT TYPE	AVAILABLE / REQUIRED INFOs
EXTERNAL CAUSE	STRUCTURAL ISSUES			
	CONSTRUCTION ERRORS	S | C	DETAILED	• ORIGINAL DESIGN DOCUMENTS • AS-BUILT & CONSTRUCTION DETAILS (BIM)
SCHEDULED ASSESSMENT for ASSET MANAGEMENT PROGRAMME		N | S | C	PRELIMINARY | DETAILED	• PERIODIC/DETAILED INSPECTION, SURVEYS OUTCOMES
	DETERIORATION PROCESSES	N | S | C	PRELIMINARY | DETAILED	• DEFECTS, DETERIORATION CHARACTERIZATION
CHANGE OF DESIGN LOADS		N | S | C	PRELIMINARY | DETAILED	INSPECTION AND TESTING RESULTS ON: • MATERIAL PROPERTIES • HAZARDS DISCRETE/CONTINUOUS (IN SPACE AND TIME) DATA FROM: • NDT/DT • MONITORING SYSTEMS
CHANGE OF HAZARDS (e.g. landslide, accidental actions)*		S | C	DETAILED	
RETROFITTING		S | C	DETAILED	
NEED FOR EXTENSION OF WORKING LIFE		S | C	DETAILED	

*[IM-SAFE integration to CEN/TS 17440]

Figure 3 – Need for assessment in time and available information.

THE AMOUNT OF INFORMATION NEEDED FOR ASSESSMENT

The process of collecting information, assessing structural performance through the data analysis and planning repair and strengthening activities is a decision procedure which aims to identify the most effective investigations and interventions required to satisfy the target reliability requirements to the use of the structure and/or to reduce the uncertainties regarding its current condition and future performance. It is important that this process is optimized with due consideration of the total service life costs of the structure. Data may be gathered from the structure for condition control purposes by a variety of techniques which are used for undertaking inspections, measurements, testing and monitoring activities. Tools and techniques for inspection, testing and monitoring could involve a wide range of procedures. Typically, they are likely to include a combination of visual observations, material sampling and possibly selected non-destructive and non-invasive testing methods as well as the installation of IoT sensors for continuous monitoring. Information acquired by inspection, testing and monitoring can greatly improve the accuracy of performance prediction by more precisely assessing the variability of the input parameters, which are typically assumed to be random variables. Characterization of the structural system and of the scenarios of interest allows to define the objectives of the monitoring application. Characterization of the monitoring system, instead, involves a thorough selection of the type, level, and duration of monitoring that is required to meet the identified objectives [11]. These characteristics will highly depend on the application, that consequently will influence the types of equipment used, the sampling frequency chosen, and the strategies implemented to process the information generated. The monitoring architecture might involve a very simple and short-term controlled test, long-term monitoring with many sensors with controlled tests conducted at periodic intervals, or long-term continuous monitoring with multiple sensors. It is essential to remember these methods have a limited resolution; thus, the uncertainties associated with the inspection, testing and monitoring procedures are to be properly addressed and quantified in the evaluation of the indicators of the estimated condition of a structure. Therefore, in order to reduce both measurements and the model uncertainties, an optimization of the monitoring system is to be performed and more refined and calibrated structural models (e.g. finite element models) should be used for the assessment of existing structures. Decisions concerning structures should account for all uncertainties of relevance for their performances such as measurement error, aleatory uncertainties (inherent variability of a measured parameter - direct information), model uncertainty (when a parameter of interest cannot be measured directly so that a relationship between it and the corresponding measured parameter is needed - indirect information), statistical uncertainty (due to a limited number of measurements) or other epistemic uncertainties (lack of knowledge on the structural system (as-built), or numerical modelling uncertainties). Uncertainties can be reduced or mitigated by updating the available information on the basis of measurements and inspections.

MONITORING AND INSPECTION LOCATION

The decision on the use of the monitoring system and its characteristics is based on an in-depth cost-benefit analysis, on the basis of which it is possible to identify, in realistic terms, the role to be assigned to the monitoring system and to design the sensor network and, more generally, the whole system in order to be proportionate to the benefits to be obtained. As part of the design of a monitoring system, key aspect is related to the number and positioning of the measurement points. Locations where inspection, testing and condition monitoring activities are to be undertaken must be carefully selected so that the desired information about the deterioration of materials and/or structural performance can be obtained, keeping in mind factors such as the likely mechanism(s) and rate of deterioration, the environmental conditions, the conservation strategy and tactics and the inspection testing and monitoring regimes defined at the time of design or redesign. The identification of vulnerable elements/zones for different structural typologies, or for specific structures, provides a good guidance to select the inspections locations or the monitoring areas of major interest, so that the structural adverse response during the occurrence of a hazardous event can be efficiently analysed. The vulnerable zones are defined as the physically distinguishable parts of an entity (e.g. network, object, component or element, or the parts thereof), for which change of its condition or other direct consequences of a hazardous event have the largest impact on its performance. Each vulnerable zone may be related to several risks and failure modes and can represent crucial monitoring or inspection location. Several methods for the characterization of the vulnerable elements of a structure are available, such as robustness related detection method, sensitivity related detection method, force and loading based vulnerability analysis, deformation or performance-based vulnerability analysis. When evaluating vulnerable areas, it is important to take into account that some vulnerable areas can develop only with the aging of the structure or also the occurrence of degradation processes. Some vulnerable areas also cannot be assessed by visual inspection or monitoring because they are not accessible. In such cases, modelling or advanced inspection techniques are recommended for the assessment.

CURRENT AND FUTURE USE OF MONITORING DATA IN THE STRUCTURAL ASSESSMENT PROCESS

Performance verification using a data-informed approach based on the information collected from inspections, testing and monitoring is still an open research topic as more advanced knowledge is gained in the fields of data processing, monitoring and maintenance planning. Similar to the design of new structures, when assessing existing structures, it should be verified that, with an appropriate reliability level no limit state is exceeded for all relevant assessment situations. As illustrated in Figure 4, the assessment can be performed following different methods of progressively decreasing complexity (risk-based, reliability based and semi-probabilistic methods). The most accurate way of assessment would be to explicitly consider updated load and strength variables applying reliability methods or risk-based decision procedures. However, such methods and procedures are time-consuming, calling for a specific operational knowledge of probabilistic methods, and are preferably used in special cases, such as for strategic structures, in case of uncertainties outside the usual ranges, in cases of severe failure consequences or insufficient robustness, or for decisions regarding a whole group of similar structures (e.g. calibration of partial factors). To verify if existing structures fulfil the reliability requirements for all assessment situations, the semi-probabilistic methods are usually used: depending on the problem at hand either verifications are performed in the partial factor format involving updating the characteristic values of the basic variables and partial factors based on updated information is used or verifications are based on the updated FE nonlinear models in used in the context of global resistance format .

As part of the updating procedure, deterioration due to environmental influences, repeated actions or use-induced wear has to be taken into account, as well as its cumulative process that can adversely affect the reliability of existing structures. When assessing existing structures, the simplifications of neglecting the influence of deterioration (assumed for the design of new structures) is not appropriate as these are already affected by damage mechanisms. Reliability requirements should be verified for the combined effects of cumulative deterioration and the relevant actions likely to occur during the remaining service life. Models should explicitly take into account the effects of deterioration on the resistance, including a quantification of all relevant material-specific associated uncertainties. Models should also be developed to describe the propagation of deterioration as a function of time, with the aim of predicting the condition of an existing structure over the remaining service life, going out from its actual condition at the time of assessment. Depending on the conditions to which the structure is exposed (e.g. environmental influences, repeated actions), these models should describe the onset and the rate of the cumulative processes that affect the parameters influencing the remaining structural resistance. The spatial distribution of the processes should be accounted for if relevant. The uncertainties associated with the models that describe the propagation of deterioration as a function of time should be taken into account and may be reduced by implementing structural health monitoring techniques to provide information about environmental influences on the structure, degradation processes or structural performance and their variation over time.

Use of data in performance verifications

In the following, a description of the use of data in the performance verification is provided for each of the assessment methods considered.

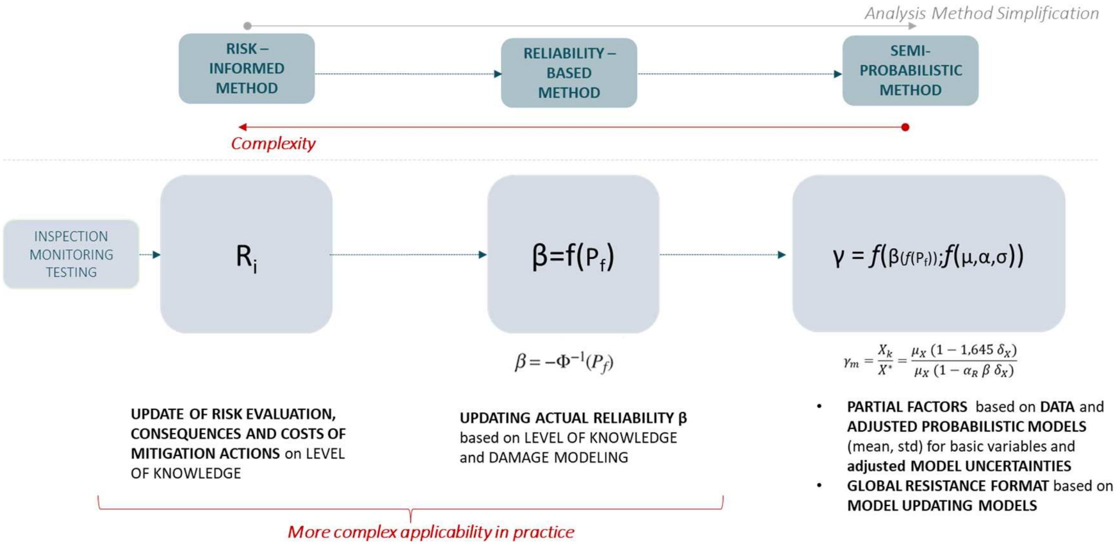


Figure 4 – Performance verification using a data-informed approach based on the information collected from inspections, testing and monitoring.

Use of data in risk-based methods

All risk management and risk assessment methods require data to identify risks, hazards, causes, consequences and/or to quantify probabilities and consequences. Therefore, all risk assessments are ‘data-informed’. Thus, it is important to be more specific about the use of data in risk management and risk assessment methods, in terms of purpose of the data, type of data being used, as well as data sources. When a quantitative approach to risk management (and assessment by extension) is undertaken, this requires quantitative description (data) of the performance of elements of the system, which is being modelled. The main variables of the performance of system and its elements are according to [12]: reliability of system elements, resistance capacity of the system elements, loads and stresses, and undesirable consequences of failure. Specifically, reliability (and failure) data are of interest because they provide the analyst information with regards to (target) reliability levels used in (risk-based) performance assessment methods. Increased level of knowledge additionally provides a better understanding of risk and costs related to risk management. The data used for the risk assessment depends on the characteristics of the system in consideration. According to [12], at least on one of the following reliability data is needed: overall failure rates, failure rates in individual failure modes, variation of failure rates with time, unavailability in terms of demand, repair times. In terms of data sources, failure data for system elements and their components are generally either experimental data or expert opinion [13]. Based on experimentally-collected failure data, a statistical analysis can be performed in order to calculate the average failure rate λ(t), which is usually the reliability measure most interesting to the analyst [12]. In order to describe the average failure rate, experimental data need to be assembled, which can be done based on laboratory testing, field data or from (historical) incident data. Data based on expert opinion can be of qualitative or quantitative nature and can be obtained from infrastructure operators, maintenance staff, management, and others. Typically, the identified experts are asked to express their opinion with regards to the average failure rate and/or to estimate the range of failure rates [12]. Since such data depends on the experience, knowledge, and ability to make judgment and convey opinions of people consulted, data based on expert opinion can be heavily subjective. Therefore, a statistical analysis may be performed to derive the point estimates or probability distributions of, for example, individual failure rates. Eventual qualitative data can be processed into quantitative information for later calculations by aggregating the expert opinions in order to achieve a sufficient level of consensus.

Use of data in reliability-based methods

Observations acquired by inspection and monitoring inform about the safety of the structure and can be explicitly utilized to update the reliability analysis and, therefore, the probability of structural failure, since they are related by the following equation, in which Φ^{-1} is the inverse standard normal probability distribution function [4,5,7].

$$\beta = -\Phi^{-1}\left(P_f\right)$$

The updating of failure probability may be performed with the following approaches: (i) direct updating; (ii) updating based on information from load testing or (iii) about the past performance.

The direct update of the structural failure probability by using new data may formally be carried out by using the basic relationship from probability theory:

$$P(F|I) = \frac{P(F \cap I)}{P(I)}$$

where F denotes a local or global structural failure; I denotes the inspection information; ∩ indicates the intersection of two events; | indicates “conditional upon”. This procedure can be applied, for example, after the execution of a proof load test.

Load testing [8], indeed, is an efficient and robust approach, since it can prove that the structure load bearing capacity is actually adequate, i.e. it can reveal its hidden capacity, and it always enables a check if the response of the structure is according to the objective of its design. Verification assisted by testing, inspection and monitoring with due consideration of load testing of structures as means of conformity evaluation is recommended in [7]. In this respect, it is possible to distinguish proof loading test and diagnostic loading test. The former is focused on improving the analytical assessment of an existing structure revealing the potential hidden safety reserve and can give important information about the effective structural performance and its actual level of safety. It is defined as the assessment of a structure under a given limit state by applying an equivalent load. The latter is focused on confirming the response of the structure against the service loads. Results from the model and the observed behaviour of the structure under a certain percentage of the design live loads are examined to verify the suitability of the design/analytical model. Load tests, that may be both static and dynamic, aim to perform a comparative analysis of the results from the model and the observed behaviour of the structure under a given load.

Lastly, for the estimation of the failure probability of a structure based on a satisfactory past performance during T years, the distribution function for structural resistance may be updated considering the cumulative distribution of the maximum load effect over the same period of T years. Satisfactory performance of a structure during T years of service indicates that, in the absence of any significant deterioration, its minimum resistance is greater than the maximum load effect applied over this period.

Once the probability of structural failure P_f has been updated, the corresponding β-value should be compared to the target reliability levels defined above, in order to define the maintenance and interventions plan.

Use of data in semi-probabilistic methods

The data-informed semi-probabilistic methods favour from the additional level of approximation via: i) updating the characteristic values of the basic variables (standard deviation and mean values of the variables distribution) and partial factors based on updated information, ii) performing a model updating procedure of an FE nonlinear model based on the results of monitoring and diagnostics load testing and verifying with global factor approach. In civil engineering, numerical or mathematical models are used to simulate the behaviour of real systems, with the purpose of performing analysis, prediction and design. In case of use of performance models for structural health monitoring purposes, it is essential to refer to calibrated models through parameter identification or estimation using model updating techniques. Examples of application of these approaches in the semi-probabilistic analysis framework (partial factor method as well as global factor method) is shown in Figure 4.

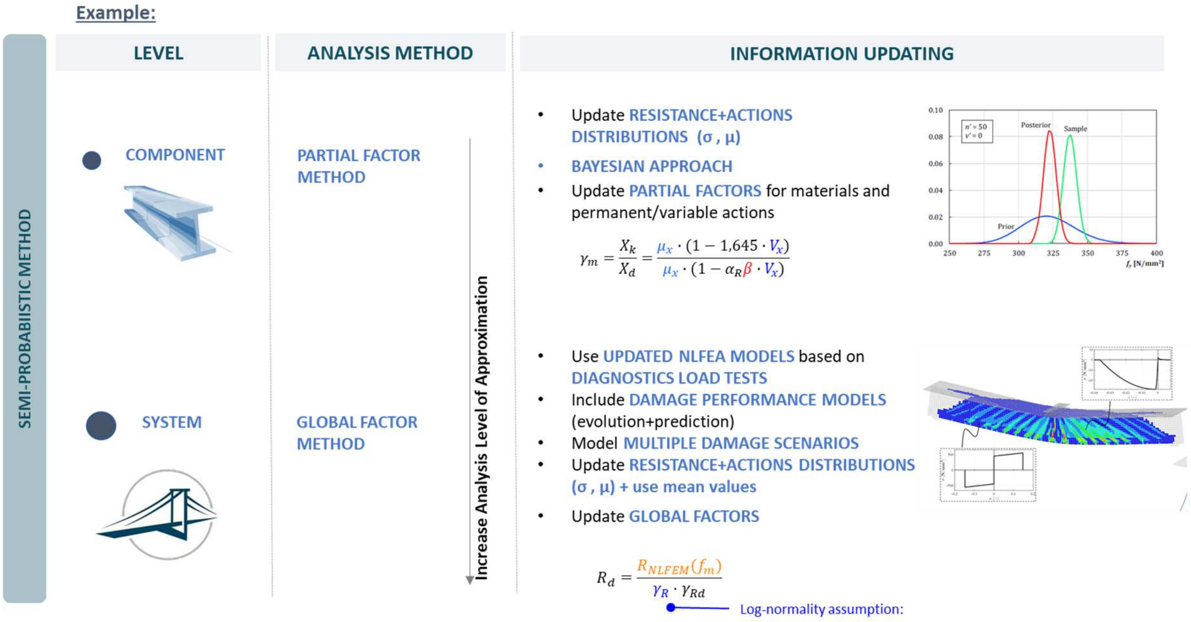


Figure 4 – Example of assessment methods and information updating procedures in semi-probabilistic methods.

The verification should follow a “Levels of Approximation Approach” (LoAA) combined with a “Levels of Knowledge Approach” (LoAKA), where the upper level should be selected depending on the significance of the uncertainties and on the ratio between costs of interventions and investigations. In this context, the choice of the parameters to be refined by site investigations or analysis should also be based on an estimate of the relationship between the uncertainties and the sensitivity of these parameters to the final result. The verification of an existing structure should start from a global condition assessment, where the site investigation should play a major role.

The information updating process may refer to classical statistical methods or to a Bayesian approach. The classical methods are based on estimating some statistics of the parameters (e.g. mean values and/or covariance matrices) so that the statistics of the output of the model correspond in some optimal way to the statistics of the observed data. This can be done analytically (i.e. classical statistical inference methods) or numerically (i.e. stochastic model inversion) [15]. The Bayesian inference approach was introduced in structural dynamics by Beck et al. [16] and complements the probabilistic model description with a probabilistic model for the error prediction of both the measurement and modeling uncertainty. Using the Bayes' theorem, prior probabilistic models, which are constructed based on the a priori available information, can be transformed into posterior models, using the available experimental data and the probabilistic prediction error model. The Bayesian approach is particularly suited for inverse problems.

CONCLUSIONS

The contribution discussed in the present paper describes the outcome of the H2020 CSA IM-SAFE EU-project with respect to the analysis of the approaches to data-informed safety assessment [4]. Attention has been given to the differences of assessment methods between new and existing structures, concentrating on the latter for the availability of additional information obtained from inspection, monitoring and testing campaigns. A detailed analysis of the main variables to consider when designing a monitoring has been provided, looking at the type of information needed for the assessment, the amount of information, the location where the information should be retrieved and the use of information in verifications. Current and future use of monitoring data in the structural assessment process has been presented, with respect to risk-based, reliability-based and semi-probabilistic performance verification methods. The contribution outlines the vision and approach developed in the currently ongoing, which aims to support the preparation of the mandate for CEN for further amendment to the existing EU standards enabling data-informed safety assessment taking into account inspections, monitoring and testing.

ACKNOWLEDGEMENTS

The authors acknowledge that this project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. The sole responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the European Union. Neither the Innovation and Networks Executive Agency (INEA) nor the European Commission are responsible for any use that may be made of the in-formation contained therein.

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