Future perspectives of standardisation for a safe European transport infrastructure

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Abstract

Aiming to ensure the safety of the transport infrastructure during operation through the improvement of maintenance policies across Europe, the European Commission opened in 2019 the call for the Coordination and Support Action (CSA) "Monitoring and safety of transport infrastructure". The main goal of this CSA is to support the preparation of a mandate for a CEN standard for the maintenance and control of the European transport infrastructure. In 2020, the CSA was granted to the IM-SAFE project consortium. Based on the analysis of standardisation needs, good practice and available knowledge and technology, the future perspectives of standardisation for the use of monitoring, inspection and testing in managing the safety risks to transport infrastructure has been studied.

This contribution presents the scope proposed by the IM-SAFE project for future harmonised European standards in the domain of monitoring, data-informed safety assessment and condition-based and risk-based predictive maintenance policies for bridges and tunnels, considering the integration of digital innovations as enabling technology.

Keywords: standardisation, bridges, tunnels, monitoring, data-informed safety assessment, maintenance.

1 Introduction

Road and railway infrastructure networks form the backbone of European transportation systems, carrying more than 80% of passenger and 50% of goods transport in Europe. Malfunction and non-availability of these infrastructure assets has huge negative impacts and long-term drawbacks on the economy and society. A variety of hazards, such as deterioration, aging, increasing trends of the loads in the past decades, insufficient inspections , inadequate maintenance, climate change and man-made related hazards lead to high risks to the safe use of bridges and tunnels. This is an urgent issue both European and global, as shown by the nearly 30 major failures of road and railway bridges and tunnels in Europe in the last two decades with the collapse of the Morandi Bridge in Genoa as the most recent disruptive event.

This contribution presents the scope proposed by the IM-SAFE project [1] for future European standards for monitoring, data-informed safety assessment and condition-based and risk-based predictive maintenance policies for concrete bridges and tunnels, considering the integration of digital innovations as enabling technology. The IM-SAFE project envisions a paradigm shift from

corrective maintenance towards preventive condition-based maintenance, which is set within a risk-based framework for maintenance management and integrated with data-informed safety assessment and maintenance decision-making. The primary objective of the IM-SAFE project is to prepare the draft input for a future European standardisation process (CEN) on:
1) structural monitoring
2) data-enhanced safety assessment of existing structures
3) maintenance of the transport infrastructure.

These three standardisation areas are highly interconnected, because the main criterion for the planning and execution of maintenance is structural safety whose evaluation can be enhanced by using monitoring data.
In the following, the needs and the scope for future standardisation regarding the three standards listed above as envisaged by the IM-SAFE project.

2 Structural monitoring

2.1 Needs for standardisation

Structural monitoring is defined as the frequent or continuous, normally long-term, observation or measurement of structural conditions, actions or structural response [2]. This information can be gathered by various conditions surveys technologies and methods, such as inspections and sensor systems. The current applications of structural monitoring in the civil engineering field are diverse and include:

- monitoring of actions, action effects, evolution of damages and deterioration processes
- monitoring during construction and operation phases
- monitoring during static and dynamic field tests
- monitoring as operational mitigation measure.

The current state of standardisation on monitoring of civil structures consists of guidelines published in a limited number of European countries [3-5] and few ISO standards [6-7]. These documents provide the user with information and guidelines on the current monitoring technologies, execution of the monitoring activities and data analysis. However, the current standards and guidelines do not address sufficiently the complex combination of decisions that would result into gathering relevant and sufficient information about the condition of the structure for the purpose of asset management.

2.2 Proposed scope of future standardisation

In the IM-SAFE vision, standardisation on structural monitoring should consider and embrace the continuous and fast development of new condition survey technologies and data analysis methods. A future-proof standardisation process can be achieved by providing principles and requirements as well as guidance for the successful implementation of monitoring activities. The future standard on structural monitoring should focus on the following topics:

- the decision-making process regarding the choice of the most appropriate monitoring strategy for the case under consideration
- the requirements for installation and operation of the monitoring system aiming to guarantee reliable data
- the analysis of the monitoring data for extracting useful information for the safety assessment and risk management of structures
- data management for future use

The decision-making process regarding the choice of the monitoring strategy involves several steps, including:

- definition of the objectives of the monitoring activities
- choice of the monitoring type (e.g. periodic / continuous)
- choice of the measured quantities
- definition of the required measurement accuracy
- selection of the monitoring technologies
- design of the monitoring system, including amount and placement of the monitoring devices
- evaluation of alternative monitoring strategies

The clear and detailed definition of the monitoring goals is the key step which determines the information needed to reach them. The monitoring regime (periodic or continuous), the measured quantities and the required measurement accuracy follow from the information required to meet the goals of the monitoring activity. The choice of the monitoring technology, or the combination of different monitoring technologies, depends on technical and economic aspects. The technical aspects include the measurement type (static or dynamic, local or global, short-term or continuous, etc.), the measurement range and accuracy, the sensitivity to the environmental conditions and the ease of installation of the measurement device. Economic aspects include the cost of the monitoring system, the lifespan of the technology and required maintenance and the benefit of the acquired information on the expected lifecycle costs of the structure under investigation. Acknowledging that different kinds of expertise and approaches are currently used to choose the monitoring strategy, a multi-level approach, ranging from engineering judgement to the Value of Information concept, will be proposed.

The success of monitoring activities depends also on the correct installation and functioning of the hardware and software for the intended monitoring period. For this reason, the IM-SAFE project will address requirements and recommendations on the post-installation verification, management and maintenance of the acquisition system.

Regarding the analysis of the monitoring data, two aspects will be considered: data processing and data analysis. The collected data need to be processed before being used for the analysis of the condition of the structure, the updating of load, load effects and performance models. The technical input of the IM-SAFE project will consist of the key principles and requirements regarding the identification of outliers, removal of the environmental effects from the raw data and data validation.

Data analysis comprises the methodologies applied to translate the measured data into information about the current condition of the structure. Among the applications of monitoring data, the focus of the IM-SAFE project is on updating of loads and structural diagnostics. The latter concerns:

- updating of structural models
- detection, localisation, quantification and prognosis of damage and deterioration processes

When there is evidence or suspect that the structure is damaged or deteriorated, structural diagnostics can be supported by monitoring associated performance indicators comparing reference measurements with measurements based on the current condition. The IM-SAFE input for standardisation will consist of principles, requirements and criteria for the selection of the most appropriate data analysis methods.

The data collected during the monitoring activities are key inputs for asset management. Therefore, the storage of these data in the through-life information management systems should fulfil requirements aiming at data interoperability and easiness of retrieving the relevant information by different experts and data models (e.g. BIM).

3 Data-enhanced safety assessment of existing structures

3.1 Needs for standardisation

In the last decade, several European countries have developed national standards and guidelines regarding the assessment of and intervention on existing structures. The largest part of the standardisation effort has been devoted to the critical aspects of the structural assessment of bridges and only partly to the development of a reliability framework specific for existing structures. CEN/TC 250 has recently published the technical specification CEN/TS 17440:2020 “Assessment and retrofitting of existing structures” [8] resulting from the mandate M/515 EN “Mandate for amending existing Eurocodes and extending the scope of structural Eurocodes”. This technical specification provides additional provisions to EN1990 [9] regarding the assessment of existing structures.

Even though structure-specific information plays a key role in the safety assessment, only the use of direct information for the determination of the assessment values of the material strength and actions is widely addressed by the available standards and guidelines. The utilisation of other sources of information, such as proof-load tests, inspections and monitoring, is treated less in the detail.

3.2 Proposed scope of future standardisation

It is envisaged that the future standardisation on the safety assessment of existing structures will consist of amendments to the current Eurocodes. Even though several interdisciplinary aspects, such as the behaviour of structural elements under static and dynamic actions and soil-structure interaction, are involved in the safety assessment, the scope of the IM-SAFE proposal is limited to the amendments to the following Eurocodes:

- EN 1990 “Eurocode - Basis of structural design”
- EN 1991-2 “Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges”
- EN 1992 “Eurocode 2: Design of concrete structures”
- EN 1993 “Eurocode 3: Design of steel structures”

The objectives of the IM-SAFE proposal on this topic are:

- to enable full utilisation of the information gathered from inspections, testing and monitoring for the safety assessment of existing bridges and tunnels
- to address the explicit consideration of deterioration and damage in the safety assessment
- to address the definition of threshold values of the structural response for assessing safety during operation.

Regarding the use of structure-specific information for the safety assessment of existing structures, the extension of the approach developed in the technical specification CEN/TS 17440:2020 “Assessment and retrofitting of existing structures” for updating the failure probability and the basic variables of the limit state functions based on direct information (e.g. measured actions and material properties) will be extended to indirect information (e.g. information on parameters not directly involved in the limit state functions such as the outcomes of inspections, monitoring and testing).

Furthermore, the IM-SAFE proposal for future standardisation will produce also provisions for the use of the outcomes of proof-load testing in the safety assessment at the semi-probabilistic level (e.g. through the updating of the assessment value of the resistance). Proof loading is currently used for evaluating the compliance of a structure (or elements of the structure) with the limit states of interest. When referring to the ultimate limit states, proof loading can be used as a complete assessment by itself in place of the model-based assessment [10]. The observation that the structure (or elements of the structure) does not fail during the test and no significant signs of distress are observed verifies the non-exceedance of the limit state, provided that the proof load level is chosen sufficiently high for the considered limit state. Even in case that the proof load level cannot be reached because one or more stop criteria are exceeded, the proof load test provides only a lower bound of the load bearing capacity.

Proof loading is not the only type of load tests currently applied to bridges. Testing for the static and dynamic structural properties might be applied in case of suspected or evident deviations from the design assumptions (e.g. deterioration) or to increase the understanding of the actual behaviour of the structure. In addition, diagnostic load tests can be used to calibrate models for structural assessment based on measurement response leading to more accurate predictions of the structural performance. Provided that the load test conditions cover all relevant aspects for the evaluation of the load effects in the assessment procedure, the model uncertainty of the load effect model can be updated based on the measurements. An approach for the update of the partial factor of the model uncertainty is given in [11].

Monitoring of actions can be used to determine the design value of the loads, according to the approach presented in CEN/TS 17440:2020 “Assessment and retrofitting of existing structures”. The IM-SAFE input for standardisation will focus on the procedure for assessing the adjustment factors given in EN 1991-2 “Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges” based on actual to traffic load data.

In case that time-dependent deterioration (e.g. fatigue, reinforcement corrosion, or ASR) or damage due to accidental actions are detected, their effects on the structural resistance need to be considered in the assessment. Deterioration and damage leads to a time- and spatial-dependent reliability problem. As a result, not only the current condition is of importance, but also the prediction of the future condition must be taken into account in the safety assessment. In case of deterioration, not only predictive models and information gathered from inspections are required, but also the safety framework has to enable the consideration of such models and information. At the same time it is recognized that the currently available deterioration models are characterized by large uncertainties due to the complexity of the processes they aim to describe. In addition, these models do not cover to sufficient degree of accuracy all structural effects of deterioration (e.g. no established models are available for the reduction of reinforcement ductility or bond due to reinforcement corrosion) and information about the current condition of the structure may not be sufficient to avoid unnecessary conservativism of the assessment process when those models are applied.

Therefore, the IM-SAFE project will make a proposal for amendments to the material Eurocodes EN 1992 and EN 1993 aiming to highlight the aspects of resistance models with respect to the structural implications of damage and deterioration. Where possible suggestions on the implementation of state-of-the-art models for damage and deterioration in the safety verification will be provided. In addition, the explicit reliability verification including damage or deterioration and the principles to account for damage and deterioration in the partial factor method will be addressed (EN 1990 "Eurocode - Basis of structural design").

Permanent monitoring in operation enables the immediate notification of the occurrence of a change in the condition of the monitored structure. In case of structures at high risk, alarm thresholds are used to alert the asset owners that the structure is becoming unsafe to use in case the structural response exceeds the threshold. Even though this approach is frequently used to ensure safety during operation, there is no guideline in the standards on how to set the threshold. For this reason, the IM-SAFE project will propose the criteria and requirements for setting alarm thresholds. The definition of alarm thresholds is a decision problem that should consider:

- the limit state conditions considered critical for the monitored structure
- suitable indicators (or a set of indicators) sensitive to change in condition with respect to the chosen critical limit state conditions
- knowledge of the hazards-related events that can affect the safety of the structure
- prediction of structural performance and safety for the specified hazards-related events
- the time needed by the asset owner to intervene before the condition of the structure becomes unacceptable from the safety point of view.

In addition, the IM-SAFE project will propose a differentiation of reliability requirements between the assessment of the fitness-for-use of an existing structure during operation and the design of structural interventions. While human safety is the minimum requirement during operation, economic considerations (e.g. the higher costs of safety measures for existing structures compared to new ones) might be governing the reliability requirements for the design of structural interventions.

Reliability requirements are linked to a reference period. While 50- or 100-year reference periods are commonly chosen for the design of new structures, the 1-year reference period is more suited for the through-life management of the safety of existing structures.

4 Maintenance of the transport infrastructure

4.1 Needs for standardisation

Decisions on maintenance of bridges and tunnels in the European countries are supported by guidelines drafted at the national or even by the infrastructure operators, leading to a variety of ad-hoc approaches from corrective to preventive maintenance. Even though the guidelines give attention to structural deterioration and some of them implement simplified risk-based methodologies for prioritisation of interventions, it appears that the standardisation on maintenance and the use of information from inspection, testing and monitoring are not harmonised across Europe. Therefore, there is the need for a European standard covering two main goals:

- to promote the implementation in the long term of risk-based predictive maintenance strategies for bridges and tunnels
- to provide the asset owners with guidance on the use of inspection, testing and monitoring for the risk management of bridges and tunnels

4.2 Proposed scope of future standardisation

Through-life management of the transport infrastructure comprises a variety of activities aiming to ensure that all relevant performance requirements are met during the whole lifecycle. As part of the through-life management process, the maintenance management process and maintenance strategies have to be defined. The maintenance management process entails the prioritisation of the assets to be targeted by maintenance activities. Once this process is defined, the proper maintenance strategies have to be selected.

The technical input developed by the IM-SAFE project on maintenance focuses on the decision-making process regarding preventive maintenance to guarantee adequate through life-safety of the transport infrastructure. Other reasons triggering maintenance interventions, like road safety, are not covered by the IM-SAFE project. The design and execution of interventions are as well out of the scope of the IM-SAFE project.

A risk-based approach is proposed for the maintenance management aiming to define priorities among the stock of assets. The analysis of risks needs to consider the hazards to which the assets are exposed (e.g. deterioration processes, loading, etc.), the likelihood and consequences of the identified adverse events with respect to performance criteria and requirements of the transport infrastructure network, such as reliability, availability, maintainability and safety.

After the prioritisation analysis is performed, the maintenance strategy (corrective or preventive) is chosen. The focus of the input for standardisation will concern the principles and criteria for the selection of the optimal strategy for the different components of the assets. For this purpose, maintenance categories will be proposed to differentiate between situations in which proactive, reactive and no maintenance strategies are feasible depending on the performance requirements, risks and the accessibility for inspection and maintenance activities. Among the maintenance strategies, the risk-based approach to planning of condition survey and maintenance activities will be considered.

Another aspect considered in the input for future standardisation is the through-life management documentation. The information used to support decisions regarding inspections and maintenance consists of several documents including design and construction documentation, photographs and reports of inspections, monitoring data, maintenance reports.

5 Conclusions

The IM-SAFE project envisions a paradigm shift from the time-based/corrective maintenance towards condition- and risk-based/predictive maintenance through data-informed decision-making enabled by new and harmonized European standards on structural monitoring, data-enhanced structural assessment and maintenance of the transport infrastructure. The key elements of the future-oriented standardisation for transport infrastructure shall comprise (i) integration of condition- and risk-assessment in the lifecycle-oriented maintenance and management of the assets, (ii) data-informed assessment of the structural performance, (iii) condition assessment and diagnostics of infrastructure based on reviewing the structure- and/or network-specific data gathered from inspection, testing and monitoring. The scope of future standardisation proposed by the IM-SAFE project is outlined in this paper.

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