Standardisation in Monitoring, Safety Assessment and Maintenance of the Transport Infrastructure: Current Status and Future Perspectives

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Abstract. This contribution is outlining the vision and approach developed in the IM-SAFE project towards the standardisation of monitoring, data-informed safety assessment and predictive maintenance policies of bridges and tunnels considering the integration of digital innovations and reports on the initial activity in the IM-SAFE that is focused on the analysis of actual and future context of monitoring and on the formulation of requirements and needs for future European standardisation.

Keywords: Standardization, Monitoring, Safety, Maintenance, Eurocodes

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. In particular, large infrastructure assets are crucial for the availability and safety of the Trans-European Transport Network (TEN-T) that has over 1234 km of large bridges (bridges with >100m span) and 775 km of tunnels. Malfunction of these infrastructure assets will cause huge negative impacts and long-term drawbacks on the economy and society [1]. Bridges and tunnels which are critical elements of the transport infrastructure networks, have in many cases reached their design service life and keep ageing. Besides, most bridges currently carry significantly more vehicles / traffic loads than what they were originally designed for. Such a condition brings high safety risks. At the same time, resources and capacity for conservation and care are too limited and should be used in an optimised way to counteract the growing backlog of maintenance. Maintenance deficiency accelerates the structural deterioration and the safety risk of infrastructure. This urgent issue is both European and global: in the last two decades there have been nearly 30 major failures of road and railway bridges and tunnels in Europe with hundreds of people killed and injured. The collapse of the Morandi Bridge in Genoa, Italy (2018, 43 people killed) has led to a year-long state of emergency in the Liguria region, an extensive analysis of the structural failure, and widely varying disputes of liability. Such incident cannot be singled out: in the last two decades, around 20 bridges in different European countries (Italy, France, Portugal, Spain, Denmark, Finland, Norway, Ireland, UK, Greece, Romania, Czech Republic) have collapsed or severely damaged with nearly 120 casualties. Beside bridges, similar concerns affect tunnel and other types of infrastructure. Although the most notorious examples of major tunnel disasters in Europe are related to the catastrophic fire, at the end of 2019 severe damages have occurred in the highway E26 Berté tunnel near Genoa, Italy where heavy concrete tunnel lining fell down and caused a major traffic disruption.

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.

2 Standardization outlook

Despite the constantly increasing number of examples and knowledge exchange on the use of surveying information form inspection, testing and monitoring to support the safety and risk assessment of existing structures, major challenges are being faced in establishing consensus on harmonised standards. Among other factors, the lack of consolidation of the current best practices, the limited insight into the actual state of standardisation in the European countries, and the fragmented vision on the future needs and trends of monitoring and maintenance and the barriers in political, economic, social and technical aspects play are major obstacles in creating common grounds for harmonised European standardization.

IM-SAFE envisions a paradigm shift from the time-based/corrective maintenance towards condition- and risk-based/predictive maintenance through data-informed decision-making enabled by a new and harmonized European standards. The key elements of the standardisation shall comprise (i) establishing basis for diagnostics of structure based on reviewing the structure and/or network-specific data gathered from monitoring, (ii) integrating monitoring and diagnostics with evaluation of the condition of the structures and assessment of the structural performance, (ii) introducing condition- and risk-assessment in the through-life maintenance and care of the infrastructure. Standardizing approach to monitoring of infrastructure, including a standardized digitalization, shall allow to gather relevant information for evaluation of the condition of the structures and assessment of the structural performance. Data-informed condition evaluation and assessment of the structural performance should provide basis for taking decisions with regard to through-life maintenance and care, while the main advantage of such integrated approach is that the information gathered from the structures enables timely and cost-effective assessing the actual safety and the risk levels of the structure as well as for predicting the future safety and risks. Introducing approaches based on condition- and risk-assessment to maintenance standards is aimed at early identification of problems and possible risk issues following from the condition of the structure, potentially enabling early preventive actions such as repairs, strengthening, renovations or use restrictions to be taken with minimal overall cost of ownership. In order to maximize safety, availability and cost-effectiveness of transport infrastructure over throughout is entire lifetime, condition- and risk-based maintenance strategies should be embedded in infrastructure management systems.

IM-SAFE aims to realize this vision by filling-in the gaps in the current standards and closing the gap between the standard and the practice. The objective of the first stage in the IM-SAFE project is therefore to formulate the basis the for harmonization of the rules between the EU countries by (i) evaluating the current practice in standardization, (ii) assessing the feasibility of practical implementation of state-of-the-art knowledge and novel solutions in standardized provisions for monitoring, safety assessment and maintenance of the transport infrastructure, and (iii) considering barriers to reach the consensus in the development and implementation of new harmonized standards in Europe. On that basis, the needs and the requirements for new European standards for monitoring and maintenance of the structures, and the rules in the structural design codes (Eurocodes are to be formulated. The new standards should be supported and implemented coherently by the public authorities and the industrial stakeholders across Europe.

3 The challenge of practical implementation

In engineering it is common to demonstrate the practical applicability of theory and methods by case studies. In this regard, case studies inform about potential, relevance but also about obstacles and limitations of theory and methods for solving problems in the real world. The case studies about maintenance, assessment of the structural performance and monitoring of existing bridges and tunnels that are publicly available, however, are mostly written by researchers and follow the research interest of demonstrating a particular methodology. Besides the real case addressed, these case studies often contain constructed data or assumptions to “make the demonstration work”. Consequently, case studies seldomly serve as a blueprint that can be used in a real reassessment context. Due to the progress of the project, the highlighted aspects have the status of a hypothesis reflecting the expected outcome of the formal study currently performed by the project consortium. In the following the main challenges and obstacles in real maintenance, structural reassessment and monitoring situations are highlighted and briefly discussed.

3.1 Challenges of practical maintenance of the transport infrastructure

Maintenance is understood as the "Combination of all technical, aministrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (EN 13306). For bridges and tunnels the required function is the safe accommodation of a specified traffic volume over time and the associated states are thus related to traffic safety (the expected accident rate is sufficiently low) and structural safety (the expected probability of structural failure is sufficiently low).

Infrastructure owners are responsible for maintenance and often follow up safety requirements by standardized inspection protocols where observable performance indicators are assessed and reported over time, either following a predefined and regular or adaptive schedule. Appropriate maintenance strategy shall be chosen for the management of the infrastructure, with suitable maintenance tactics (e.g. time-based, condition-based or risk-based maintenance) being chosen for implementation. A proactive maintenance strategy is desirable as it enables early identification of problems and possible risk issues following from the condition of the structure, potentially enabling early preventive actions to be taken to minimise the overall cost of ownership. In the current practice, proactive maintenance strategies are increasingly used. However, current decision-making processes with respect to maintenance activities are lacking a solid rational basis, and thus, often taken ad-hoc without duly considering the condition data and the outcome of safety and risk evaluations. In the condition-based asset management establishing the adequacy of the structure for current and future service, is judged by its ability to comply with the specified requirements related to its condition. Such requirements may be expressed e.g. in term of key performance indicators (KPIs) with the associated criteria, chosen considering the potential future development of deterioration or damage, actions on structures and the interaction with system limitations relevant for the structure. In the risk-based asset management, the outcome of safety evaluation is the basis for risk analysis which in turn form the basis for decision-making with regard to maintenance. However, in the current practice risk-based decision-making is not facilitated by standardised approaches, harmonised on European level.

3.2 Challenges of practical assessment of safety of existing structures

The need for reassessment is in general based on doubts about the structural performance and this can have several reasons as change of use/loads, detected or suspected damage or deterioration process, etc. Structural performance might refer to the absence of different 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 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). Requirements on structural performance can be formulated by normative direct assessable limits. E.g. a limit on maximum observable crack width in concrete structures. The detection of an exceedance of limits might initiate mitigation actions as e.g. physical intervention, or the initiation of a more careful analysis of the structure. For adverse states with larger consequences as the structural failure limit state, requirements on structural performance are expressed as explicit reliability criteria for structural safety.

Since 2010 the Eurocodes have reached the final stage of national implementation by the Member States as they are now replacing all national standards, assuring more uniform safety levels for buildings and critical infrastructures within the EU. For new structures reliability criteria are formulated and the target reliability indices for three different consequence classes are given explicitly (EN 1990:2002). However, in practical structural design it is assumed that these reliability requirements are complied with when applying the partial safety factors and design equations given in the code, i.e. the reliability requirements are only considered implicitly. For the assessment of the reliability of existing structures, however, the partial safety factors and design equations given in the code are no longer valid and cannot serve as an implicit poof of compliance. In the absence of a partial factor format that is applicable for the assessment situation at hand, the engineer is left with some ambitious challenges to evaluate the compliance with the reliability criteria:

- To which event should the reliability criterion be related to? Commonly, limit states on which basis reliability can be assessed, represent single failure modes. And the realization of failure modes implies a large possible variety of consequences. Consequences, in turn effect the criterion for reliability. The representation and analysis of failure of the entire structure, i.e. a critical combination of failure modes, often requires considerable efforts and is not always feasible.
- The specification of the reliability criterion itself is also very difficult in a structural assessment situation. The reliability criteria for new structures as specified in the design standard might be only of limited use as it not only refers to different consequence classes but implicitly also to the models, uncertainties and design cost (risk mitigation costs). These aspects might be entirely different for an assessment situation of an existing structure. The models to represent the limit states are often much more detailed in an assessment situation, and uncertainties are surely also different (e.g. larger in the presence of an unclear and spatially variable deterioration process). The costs for increasing the reliability are also much different: whereas in the design and planning phase the increase of reliability requires only the investment in e.g. some percent more reinforcement, for an existing structure the reliability can often only be increased by expensive strengthening measures. This clearly affects the magnitude of a reasonable reliability criterion.
- The limit states should be formulated such that they contain the suspected damage or deterioration mechanisms. This is particularly challenging when damage or deterioration mechanisms vary in space, as this would possibly necessitate an explicit representation of the complex system interactions in the structure (i.e. prohibit the simplified representation by a few single failure modes).
- Based on the developed limit states, in case of explicit reliability verification, the prior reliability has to be computed, i.e. the reliability that results when all random

variables (or processes) in the limit state represent the prior knowledge (the knowledge that did lead to doubts about the structure and initiated the reassessment). The knowledge is in general scarce and the uncertainties are large. Experience shows, that the quantification of these large uncertainties is particularly difficult.

- The explicit reliability verification requires a very high expertise level that is at present not common to the engineering practise. Moreover, suitability of the high level of the refinement in the reliability verification is very much depending on the availability and relevance of the information that is an can be obtained about the loads and load effect on structure, and on the justification of the costs of the effort-demanding analysis. It is therefore essential to provide the engineer with sufficient flexibility in choosing his approach, both with respect to the verification format for compliance check and level of approximation of the load and resistance models used for the evaluation of structural performance.

3.3 Challenges of practical data acquisition and sampling

The state of the structure has to be examined by inspections and measurements. 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 e.g. (i) the usage conditions and the nature of the threats / hazards posed, (ii) the plausible mechanisms and rate of development of deterioration or damage, (iii) the locations of greatest hazard and highest vulnerability of the structure to deterioration or damage, (iv) the conservation strategy and tactics, and the condition survey regimes defined at the time of design or assessment.

Knowing that inspections and measurements impose additional costs of ownership, they should be planned carefully and relative to the expected information content they would supply. Thus, the information of the inspection and measurement data has to be connected to the variables in the condition-, structural performance or risk evaluations. This is feasible when realizations of these variables are directly measured or observed. In general, however, measurements or observations are only indirectly informing about the variables in the limit state and this requires the awareness about the corresponding likelihoods, i.e. conditional probabilistic models representing the likelihood of a measurement by given realization of the variable of interest. In general, these likelihoods are very difficult to specify/estimate. Another big challenge is associated with sampling. The principle purpose of measurements and observation is to inform about variables that are relevant for the evaluation of condition or assessment of structural performance. The sampling, i.e. how, where, when, how many data is collected aims at the representation of the relevant population that the variable represents. Representative sampling is particularly difficult in this context.

The above highlighted challenges are all demanding and might suggest that they are impossible to overcome. The very basic character of the problem, i.e. it has to be decided whether or not a structure meets the specified performance requirements during the use stage prohibits this conclusion. The decision has to be done. And this requires that the above challenges are tackled by justifiable assumptions. An extension of structural standards for monitoring and data-informed evaluations should assist the engineer by making correct choices, without unnecessary limiting the choice of surveying technologies for data collection.

4 Status of standardisation

An initial activity in the IM-SAFE project is to create an overview of the current state of the art as represented by standards, guidelines and other regulations aimed to identify the normative gaps. The preliminary insight into the current state of standardisation is presented in the following with focus on those standards that address at least partly the challenges outlined in the previous section of this paper. The overview focuses on the following aspects:

- maintenance of bridges and tunnels
- assessment of existing structures
- structural monitoring

Even though international standards providing definitions, principles and frameworks for asset management (e.g. [1]) and risk management (e.g. [2, 3]), and European standards on maintenance (e.g. [4, 5]) exist, decision making regarding maintenance of bridges and tunnels is regulated on national and even on local level (infrastructure operators). Nevertheless, the most recent national guidelines implement lifecycle-oriented management approaches and predictive maintenance strategies . For example, the guidelines in the UK for the management of bridges (e.g. [6-8]) make use of a risk-based approach to support decision making regarding prioritisation of interventions and risk management measures, including maintenance. The risk assessment is based on predefined qualitative risk evaluations depending on the bridge typology, predefined lists of hazards and vulnerable structural details, qualitative estimation of the likelihood of adverse events and consequences of these events. A variety of hazards are considered in terms of material, durability and structural deficiencies, insufficient past maintenance and incomplete past assessments. Information about the structural conditions from inspections and monitoring are considered in the evaluation of the likelihood of risk events. Prioritisation of structures is facilitated by simplified risk rating indicators. While there are several guidelines focused on the maintenance of bridges aiming to ensure an adequate level of structural safety, less detailed recommendations and provisions have been found for tunnels. The reason is that maintenance of tunnels has likely to do with road safety more than structural safety.

Regarding the assessment of existing structures, the standardisation process started earlier at the national level in some countries than at the European level. As an example, the Netherlands and Switzerland developed at the beginning of last decade national standards dealing with the safety verification of existing structures. These standards

In the Netherlands, two assessment levels are defined: disapproval and repair. The first level is used to assess if the structure is fit for use, while the second one concerns the safety in case of repairs. The reliability requirements prescribed by the Dutch standards are differentiated with respect to the assessment levels and consequence class. The differentiation with respect to the assessment levels results in lower partial factors for the actions compared to those used for the design of new structures. The reliability requirements given in the Swiss code for existing structures depend on the efficiency of the interventions and the consequences of structural failure, following the approach of the Joint Committee on Structural Safety [14]. While these standards provide rules for updating actions and material properties, the consideration of deterioration in the safety assessment is addressed by means of generic principles. On the contrary, the British guideline "CS455 The assessment of concrete highway bridges and structures" provides detailed guidance for assessing the resistance of existing concrete structures affected by corrosion of the reinforcement or degradation of concrete. As an example, guidance is given about the measurement of the bar width and the assessment of the residual cross-sectional area of the reinforcement bars in case of corrosion of the reinforcement. With regard to the future development of deterioration, the guideline suggests to use available data, including any previous investigations and monitoring, to estimate the corrosion rate.

The most recent standardisation documents on structural monitoring consists of a limited number of international standards (e.g. [15, 16]), national standards (e.g. [17-19]) and guidelines (e.g. [20]). In addition, there are standards and guidelines on the use of monitoring data for supporting the management of the transport infrastructure (e.g. [21]). These standards have been analysed with respect to the following aspects:

- definition of monitoring
- objectives of monitoring
- accuracy requirements
- guidelines on the design of the monitoring system
- guidelines on data acquisition, cleansing and pre-processing
- guidelines on use of monitoring data for structural diagnostics, safety evaluation and/or asset management

Standards and guidelines define structural monitoring as the automated, temporary, periodic or continuous observation of the condition of structures by means of sensors, while the British guideline [21] includes also visual inspection as source of information.
When referring to the objectives of monitoring, standards and guidelines mention the identification of deterioration or damage, the control of the condition of the structure in operation and providing information to support maintenance planning. Furthermore, some standards, like the Chinese and the Austrian ones, include the control of the structural condition during the construction phases in the list of objectives, in particular for structural typologies or structural dimensions considered close to the limits of the scope of the current design standards.

In terms of measurement accuracy, the Chinese and the ISO 4866 provide specific accuracy requirements for specific applications and sensing technologies in terms of percentage of the full scale and in terms of the frequency resolution. Other documents, like the Italian and SAMCO guidelines, provide guidance on the specification of the required accuracy depending on the problem at hand and the objective of the monitoring activities.

The Italian guideline is the only document among those analysed providing a detailed appraisal of the principles underlying the design of the monitoring system. These principles include the knowledge of the structural behaviour to be monitored, the physical properties to be measured, the choice of the data analysis methodologies and the decisions that should be supported by the monitoring system.

Regarding data acquisition, cleansing and pre-processing, standards and guidelines provide generic guidelines depending on the characteristics of the monitored process (e.g. low or high dynamic processes) and the external factors that might influence the measurements (e.g. temperature, noise) or faulty measurements.

Concerning the use of the monitoring data, standards and guidelines concern mainly structural diagnostic. In this respect, guidance is given in terms of the structural parameters and indicators that are affected by damage and deterioration (e.g. modal parameters). In addition, the Italian guideline provides the explanation of the principles of model updating based on monitoring data.

5 Barriers analysis & identification

One of the major objectives of IM-SAFE project is to remove the existing Political, Economic, Societal and Technological (PEST) barriers to reach the consensus in the development and implementation of new standards in monitoring, safety assessment and maintenance of the transport infrastructure. To identify external factors that could impact standardisation, PEST analyses are conducted in the following areas:

- **Political** aspect of PEST analysis focuses on the areas in which factors such as e.g. (local, regional, national or international) government policy and/or changes in legislation may affect standardisation.
- **Economic** aspect of PEST analysis target past, current, and future economic issues, e.g. cost, financing (both public and private), insurance, taxes, economic growth, inflation and recession.
- **Social** factors that may be considered include socio-cultural elements such as attitudes and shared beliefs of end-users (society), policymakers and other stakeholders, and their resistance against changes.
- **Technological** component of PEST analysis considers the specific role and development of technologies, access to existing technological solutions, skills of professionals, research, innovation and emerging technologies.

The critical review of the outcomes of PEST analysis is a key to define the strategy to develop and adopt new European standards. As identified in the [2], in the absence of harmonised standardisation, monitoring, assessment and maintenance of transport infrastructure is covered by national legislation or recommended best-practices, and significant change is expected to take place if new standardisation is introduced. The main purpose of PEST analysis is to pave the way for wide societal acceptance and commitment for the new standards among the important target groups and key actors in all Europe's geo-clusters.

The PEST analysis has been developed in several phases, applying methodology from [3] and considering: current regulations and current practices, research and development projects (e.g.[4]), viewpoint of stakeholders, whose professional profile corresponds to the scope of analysis whose experience and knowledge provide a reliable view of the topics to be analysed, from their professional perspective. The following examples illustrate barriers to reach the consensus in the development and implementation of new standards in monitoring, safety assessment and maintenance of the transport infrastructure :

- **Political:** Lack of funding allocation from government may pose b*arriers* due to public finance rules, leading to c*onsequences and related challenges* such as cutting the budget on maintenance of existing infrastructure. Constructing new infrastructure receives more political credit and exposure than maintenance of existing structures may pose *barriers* to maintenance investment, leading to *consequences and related challenges* such as maintenance backlog.
- **Economic:** Economic policy based on "Doing nothing is cheap" may slow down decision-making, leading to *consequences and related challenges* such as delay of the important maintenance actions and decisions, to the point where they cause large negative impacts such as infrastructure failure. Economic policy base on "Lowest-cost contracts" for maintenance may result in directive approach task specification in maintenance contracts, where the asset owners specify what work will be done and how it will be done, providing little or no flexibility to the contractor in its selection of means and methods.
- **Social:** Hierarchical / flat organisations and the effect on responsibility for individuals may lead to organizational *barriers* and *consequences and related challenges* due to lack of responsibility. As infrastructure failures are rare and therefore the perception of the risk is not rational, irrational allocation of resources/attention may take place (*consequences and related challenges)*.
- **Technical:** For different technologies entering the market, main *barriers* may be posed by the resistance against new technologies, leading to *consequences and related challenges* such as lack of the implementation of the efficient technologies. Lack of government spending on technological research may create *barriers* as it may lead to lack of the arenas for innovation and hinder development of new technologies/methods for monitoring, safety assessment and maintenance

In IM-SAFE project, PEST analysis will assists in determining the uncontrollable factors that may affect development and acceptance of standardisation. The input from the stakeholders will be used to enrich the knowledge from the report by EC DG

MOVE [6] and other important reports, discussion papers position papers and foresight studies in the diverse national settings and in the EU context.

6 Summary and Conclusion

Structural monitoring and use of information obtained from monitoring in safety assessment and through-life maintenance of infrastructure is not adequately addressed in the current Eurocodes (CEN/TC 250), and the existing standards on monitoring are not consistently interpreted and implemented in different European countries due to a lack of coherent policies and the gaps in knowhow. The current standards do not reflect the full extent of existing knowledge and best practices. The high diversity of transport infrastructure assets and their environments add to the complexity for standardized monitoring. An initial activity in the IM-SAFE project is to create an overview of the current state of the art as represented by standards, guidelines and other regulations aimed to identify the gaps in the existing European standards and the monitoring practice at national level. This forms the basis for formulation of the outlook for further development of harmonised European standardisation for
IM-SAFE envisions a paradigm shift from the time-based/corrective maintenance towards condition- and risk-based/predictive maintenance through data-informed decision-making enabled by a new and harmonized European standards. State-of the-art overview of current standardisation shows that …… is challenging but feasible. The main outcome of the PEST analyses in IM-SAFE project establishing the connection between identified barriers and the recommendations to remove these barriers with standardised approaches.

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