Technical Note

Life-Cycle Performance of Civil Structure and Infrastructure Systems: Survey

Fabio Biondini, F.ASCE[1]; and Dan M. Frangopol, Dist.M.ASCE[2]

Abstract: Structural engineering is undergoing a profound change toward a life-cycle-oriented design philosophy. An effort is ongoing within SEI/ASCE to promote the transition toward this new design paradigm by using life-cycle cost analysis in conjunction with the Grand Challenge of reducing life-cycle costs of civil infrastructure projects by 50% by 2025. A Special Project approved by the SEI Technical Activities Division Executive Committee is part of this effort and includes a survey on the life-cycle performance of civil structure and infrastructure systems. The main results of the survey are presented by addressing life-cycle concepts and methods, deterioration and damage evaluation, life-cycle performance indicators, inspection and maintenance procedures, life-cycle cost analysis, and implementation in design practice. These results are expected to complement information on the state-of-research and -practice, promote a better understanding of life-cycle concepts in the structural engineering community, and foster methodologies and tools to incorporate life-cycle concepts into structural design codes and standards. **DOI: 10.1061/(ASCE)ST.1943-541X.0001923.** *© 2017 American Society of Civil Engineers.*

Author keywords: Life-cycle performance; Structural systems; Civil infrastructure systems; Structural lifetime; Aging; Deterioration processes; Uncertainty; Structural safety and reliability.

Introduction

Civil structure and infrastructure systems are the backbone of modern society and among the major drivers of the economic growth and sustainable development of countries. It is hence a strategic priority to consolidate and enhance criteria, methods, and procedures to protect, maintain, and improve the safety, robustness, durability, functionality, and resilience of critical structure and infrastructure systems under uncertainty. In this context, structural engineering is undergoing a profound change toward a life-cycle-oriented design philosophy to fulfill the continuously increasing demand from economic, environmental, social, and political needs. In particular, the advances recently accomplished in the fields of modeling, analysis, design, maintenance, and rehabilitation of deteriorating structures and infrastructures are perceived to be at the heart of a modern approach to structural engineering (Frangopol 2011; Biondini and Frangopol 2016a). These advances are of crucial importance to establish guiding policies and support decision-making processes for reliable design of durable structures and rational planning of maintenance, repair, or replacement of existing structures. This is particularly critical for bridges and infrastructure networks. According to the 2017 *Report Card for America's Infrastructure* issued by the ASCE:

> Over the past decade, there has been increased awareness of the significance of bridges to our nation's economy and the safety of the traveling public. At all levels of government, a concerted effort has been made to reduce the number of structurally deficient bridges in the U.S.—bridges that require significant maintenance, rehabilitation, or replacement. Structurally deficient bridges are not unsafe, but could become so and need to be closed without substantial improvements. . . . The most recent estimate puts the nation's backlog of bridge rehabilitation needs at $123 billion. (ASCE 2017)

ASCE is supporting the transition toward this new design paradigm and proposed the use of life-cycle cost analysis in conjunction with the Grand Challenge of reducing life-cycle costs of civil infrastructure projects by 50% by 2025.

For a rational approach to life-cycle design of structures and infrastructures, the classical point-in-time design criteria need to be extended to account for more comprehensive time-variant performance indicators over the entire service life. Furthermore, life-cycle performance metrics are necessary to effectively and quantitatively incorporate emerging environmental issues in structural design, such as the effects of global warming and climate change. Societal and political issues should also be included in framing life-cycle structural design criteria to comply with the different methods, metrics, needs, and priorities addressed by public officials, civil infrastructure users, and owners. However, efforts are still needed to implement this approach in design practice because life-cycle concepts are not yet explicitly addressed in structural design codes, standards, and specifications. In fact, the checking of system performance requirements is generally referred to the initial time of construction when the system is intact, and design for durability with respect to chemical-physical damage phenomena is limited to simplified criteria associated with classes of environmental conditions. This is clearly not consistent with the nature of the problem because a rational life-cycle-oriented design approach cannot be based on indirect evaluations of the effects of structural damage, but needs to take into account the global effects of the local damage phenomena on the overall system performance.

Further efforts in the field of life-cycle performance of structural systems under uncertainty are hence necessary to fill the gap

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SEI/ASCE Technical Council on
Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems

Task Group 1 on
Life-Cycle Performance of Structural Systems under Uncertainty

International Workshop on

Life-Cycle Performance of Civil Structure
and Infrastructure Systems

10 November 2015

ASCE Headquarters
American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, VA 20191

Fig. 1. Front cover of the brochure of the International Workshop on Life-Cycle Performance of Civil Structure and Infrastructure Systems, ASCE Headquarters, Reston, VA, U.S., November 10, 2015 (© ASCE)

between theory and practice and foster the incorporation of life-cycle concepts in structural design codes, standards, and specifications. To this purpose, research and applications are promoted within the Structural Engineering Institute (SEI) of ASCE by the Technical Council (TC) on life-cycle performance, safety, reliability, and risk of structural systems (Frangopol and Ellingwood 2010). The Technical Council, authorized in 2008, and its three Task Groups provide a forum for reviewing, developing, and promoting the principles and methods of life-cycle performance, safety, reliability, and risk of structural systems in the analysis, design, construction, assessment, inspection, maintenance, operation, monitoring, repair, rehabilitation, and optimal management of civil infrastructure systems under uncertainty. In particular, the purpose of Task Group 1 (TG1) on life-cycle performance of structural systems under uncertainty is to promote the study, research, and application of scientific principles of safety and reliability in the assessment, prediction, and optimal management of life-cycle performance of structural systems under uncertainty. The archival work product of the SEI/ASCE TC for the first five years of existence is presented in a recent state-of-the-art collection of papers representing the consensus as to the current state of the art in life-cycle performance assessment and risk-informed decision making in structural engineering (Biondini and Frangopol 2016a; Ghosn et al. 2016a, b; Lounis and McAllister 2016; Sánchez-Silva et al. 2016). The introduction to this collection is provided in Ellingwood and Frangopol (2016).

The recent activities of SEI/ASCE TC TG1 included a Special Project approved by the SEI Technical Activities Division Executive Committee for the development of a state-of-the-art report outlining the current status and research needs in the fields of life-cycle civil structure and infrastructure systems (Biondini and Frangopol 2016b). The main tasks of the Special Project were to conduct a survey and organize an International Workshop on Life-cycle Performance of Civil Structure and Infrastructure Systems, which was held by invitation only at the ASCE Headquarters in Reston, VA, on November 10, 2015 (Fig. 1). The survey was disseminated to selected researchers and experts from universities, industries, engineering firms, and agencies active in the field of life-cycle civil engineering. The objective was to obtain information about the development and the implementation of criteria, methods, and tools for life-cycle design and assessment of civil structure and infrastructure systems and to gather information about successful practices and explore avenues to overcome real and perceived obstacles to filling the gap between theory and practice. A brief overview of the main results of the survey are presented in this paper with emphasis on life-cycle concepts and methods, deterioration and damage evaluation, life-cycle performance indicators, inspection and maintenance procedures, life-cycle cost analysis, and implementation in design practice. These results, jointly with the outcome of the workshop, are expected to complement information on the state-of-research and -practice, promote a better understanding of life-cycle concepts in the structural engineering community, and foster methodologies and tools to incorporate life-cycle concepts into structural design codes, standards, and specifications.

Survey Overview

The survey was disseminated to about 400 people, including members of the SEI/ASCE Technical Council, members of the International Association for Life-Cycle Civil Engineering (IALCCE), and other selected experts in the field. The respondents have been 80 (about 20%) from 25 countries, including 70% from universities, 21% from industry and engineering firms, and 9% from agencies, including NIST, Naval Facilities Engineering and Expeditionary Warfare Center, National Research Council Canada, New York City Transit, and National Information Communications Technology Australia. Most of the respondents are affiliated to organizations with educational or research purposes and with more than 1,000 employees, but a significant response has been received also from small-sized consulting companies and organizations with less than 50 employees.

The types of structure and infrastructure systems of primary interest to the respondents are mostly bridges and buildings, but they also include offshore structures, power plants, hydraulic structures, roads and highways, railways, lifelines and power distribution systems, ports and waterways, water/wastewater utilities, and pipelines, as shown in Fig. 2. The hazards which typically affect the civil engineering structures and infrastructures of concern are mainly aging, environmental/chemical deterioration, earthquakes, overloading, and fatigue or cycle loading but also include wind/tornadoes, hurricanes, waves/tsunamis, impact, blast/explosions, fire, ice, floods, earth pressure, equipment malfunctioning, and human errors, as shown in Fig. 3. Moreover, most of these hazards may be exacerbated by the interaction with environmental factors, such as global warming and climate change, that may accelerate aging and structural deterioration and increase the occurrence of extreme weather events over the life-cycle.

The survey included 48 questions organized into seven groups as follows:

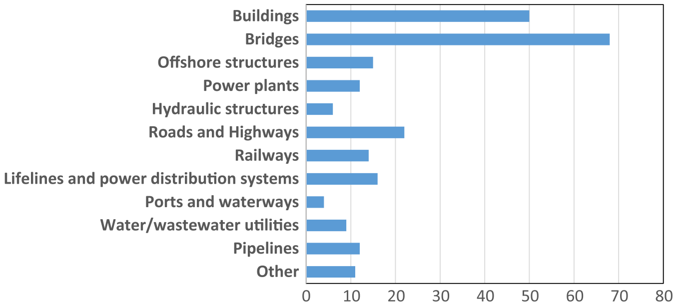

Fig. 2. Types of structure and infrastructure systems

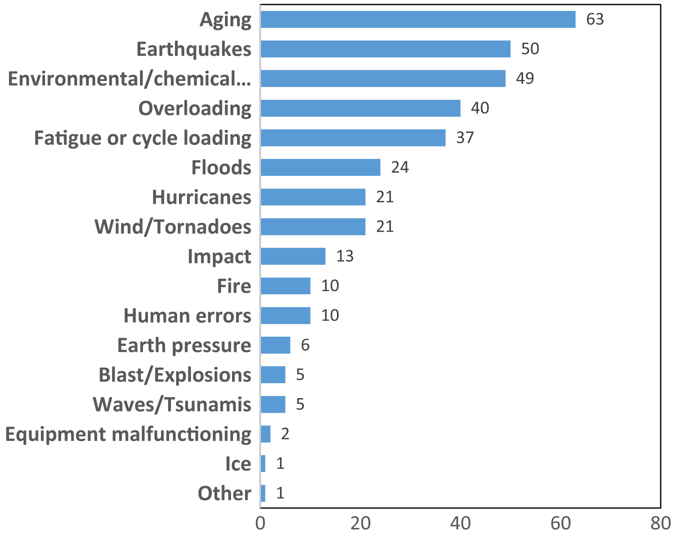

Fig. 3. Hazards that typically affect civil engineering structures and infrastructures

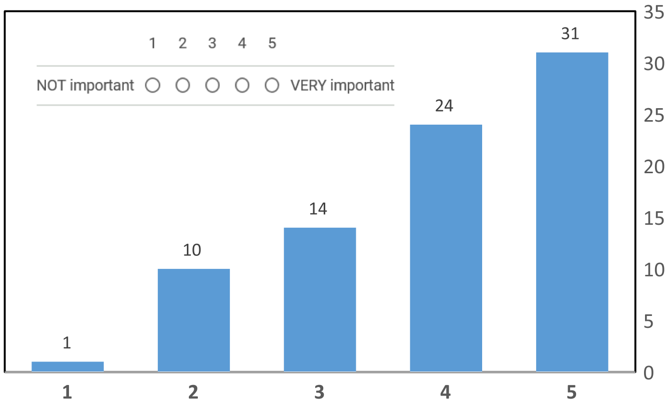

Fig. 4. Rating to the importance of life-cycle concepts in organizations

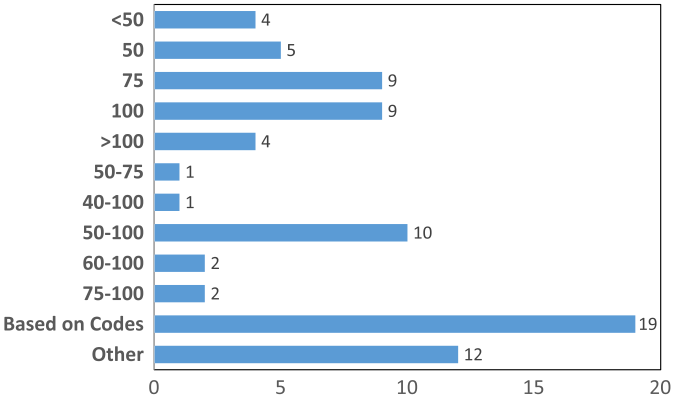

Fig. 5. Design life of civil engineering systems (years)

1. General information (8 questions),
2. Life-cycle concepts and methods (6 questions),
3. Deterioration and damage evaluation (4 questions),
4. Life-cycle performance indicators (8 questions),
5. Inspection and maintenance procedures (4 questions),
6. Life-cycle cost analysis (7 questions), and
7. Implementation in design practice (11 questions).

The full list of questions is provided in the Appendix. The main objective of the questions is to investigate the level of development and implementation of criteria, methods, and tools for life-cycle design and assessment of civil structure and infrastructure systems within the organizations of the respondents, as well as to elaborate information useful to overcome real and perceived obstacles to filling the gap between theory and practice. A brief summary of the main findings of the survey is presented in the following.

Survey Results

The need for a rational approach to life-cycle assessment and design of structures and infrastructures is confirmed by the histogram shown in Fig. 4, which indicates the overall high rating provided by most respondents to the importance of life-cycle concepts in their organizations. It is clear that life-cycle criteria must account for the specificity of the type of civil engineering systems of concern, as shown for example in Fig. 5 by the large variability of the design service life. For almost 60% of the respondents there is awareness that different life-cycle criteria are necessary also for design of new systems and evaluation of existing systems, with a wide spectrum of tools and methods that engineers should use to analyze structural performance and identify damage and possible failure modes. This is shown in Fig. 6, which indicates the need to take the effects of the uncertainties into account by means of reliability analysis methods and probabilistic simulation procedures combined with engineering experience, as well as the importance of using advanced numerical structural analysis methods to support simplified time-invariant approaches as proposed by design codes. Most importantly, large majorities of the respondents think that a probabilistic approach should be incorporated in life-cycle analysis (85%) and that a multi-hazard approach is appropriate and necessary (96%). To this purpose, probabilistic performance measures and numerical simulation methods are nowadays diffusely used (85%). It is worth noting that affiliation and country of respondents may have a role in these results. However, disaggregation of data indicated that no clear trends are identified.

A key factor in the life-cycle assessment of aging structural systems is a proper modeling of the damage and deterioration processes. Based on the results reported in Fig. 7, it is noted that the sources of damage and deterioration of materials and system components to be considered and properly modeled in life-cycle analysis mainly include corrosion, fatigue, aging, chloride penetration, and carbonation processes. However, other causes of environmental damage such as alkali–silica reaction, erosion, sulfate attack, and frost attack, among others, may often arise. Aging and deterioration are complex phenomena, and the evaluation of their effects on the system performance should account for multiple deterministic and

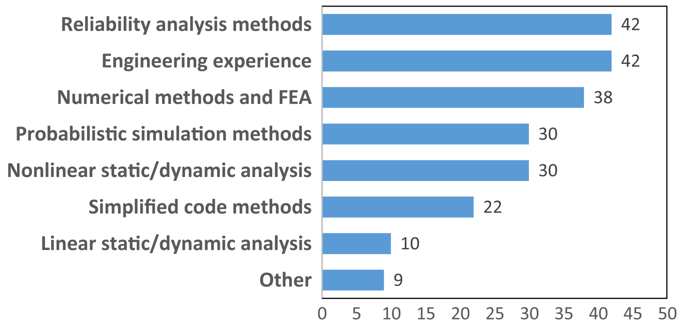

Fig. 6. Methods, procedures, and tools used to evaluate the structural performance and identify damage and possible failure modes (FEA = finite element analysis)

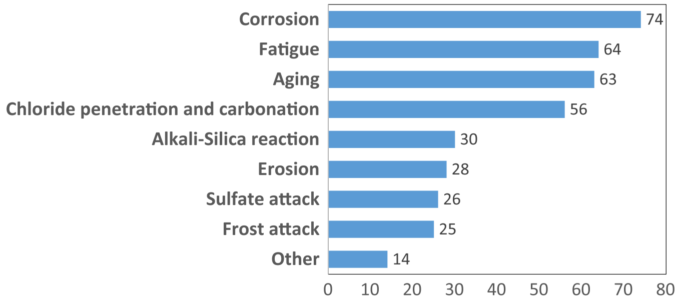

Fig. 7. Sources of damage and deterioration of materials and system components to be considered and properly modeled in life-cycle analysis

probabilistic time-variant indicators aimed at providing a comprehensive description of the life-cycle structural resources, including structural safety, serviceability, reliability, redundancy, robustness, resilience, and sustainability, as shown in Fig. 8.

The time-variant performance of structures and infrastructures must rely on effective inspection procedures, evaluation and rating systems, maintenance and repair plans. These are generally addressed in practice, as shown in Fig. 9, particularly by organizations such as agencies and authorities. The decision-making process necessary to support and properly instruct the inspection, evaluation, and maintenance processes must be based on a life-cycle cost analysis that involves the evaluation of direct costs (e.g., cost to plan, design, and build the system) and indirect costs (e.g., owner's cost, user's cost, or environmental impact). According to the respondents, in most cases both cost components are considered (64%), but frequently the cost analysis is limited to the direct costs only (31%). Also, the end-of-life removal and replacement costs are in many cases not addressed (40%).

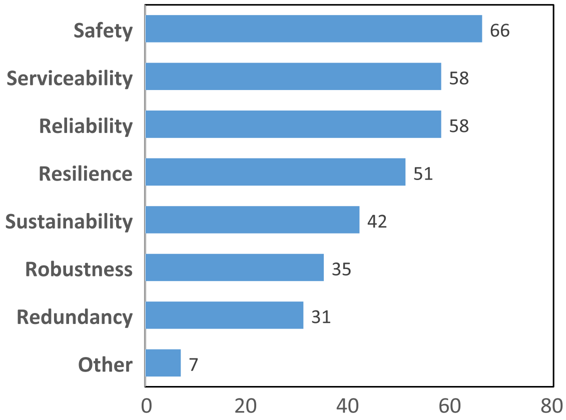

Fig. 8. Time-variant performance indicators for life-cycle analysis

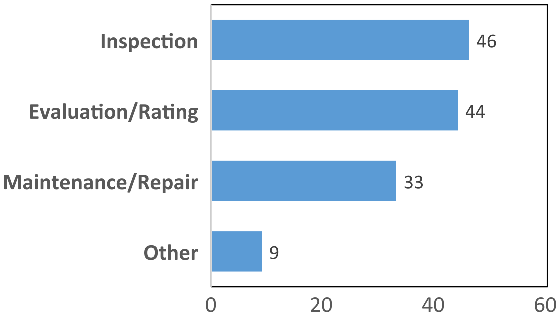

Fig. 9. Activities applied with regular frequency in organizations

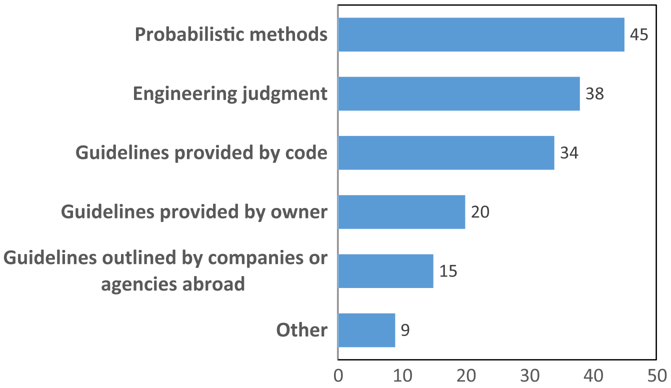

Fig. 10. Tools and resources for life-cycle analysis

Life-cycle analysis is developed in practice by using different tools, models, and/or resources. Fig. 10 indicates that the use of probabilistic methods is predominant because of the need to handle uncertainties. However, deterioration models are generally very sensitive to change of the probabilistic parameters of the input random variables, and their robust validation and accurate calibration are difficult tasks to perform because of the limited availability of data. Therefore, there is a tendency to mitigate the lack of knowledge on the uncertainty involved in the problem by using engineering judgement and relying on design codes and, when available, guidelines provided by owners or outlined by companies or agencies abroad. In fact, in most cases (76%) official guidelines to regulate the implementation of life-cycle criteria and methods are not available to practitioners working in the field. This indicates that the availability of structural design codes, standards, and specifications incorporating life-cycle concepts and addressing life-cycle methods and procedures is extremely important and represents an important target to be accomplished for the successful implementation in practice of a modern and rational approach to life-cycle analysis of civil engineering structures and infrastructure systems. This clearly emerges from the results of the survey reported in Fig. 11, which shows that advances in the standardization of the life-cycle design procedures should be complemented with an increasing awareness of the society, political system, industries, and owners. Future directions to accomplish these goals are suggested in Fig. 12, which shows that for most respondents, particularly those from the United States and Europe, ASCE 7, AASHTO, Eurocodes,

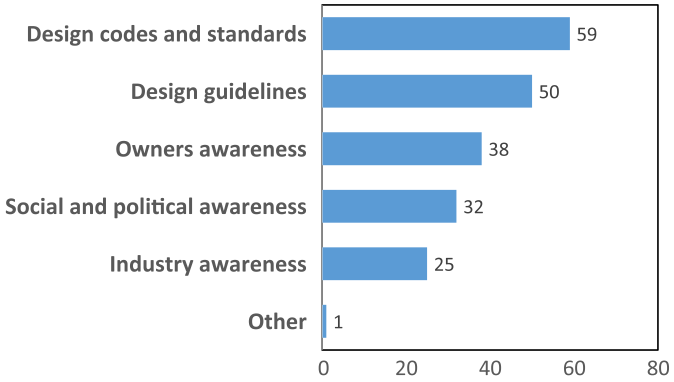

Fig. 11. Factors to be improved for promoting life-cycle analysis in design practice

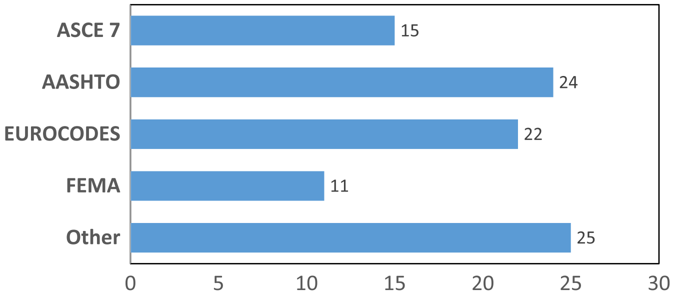

Fig. 12. Pertinent codes/standards/specifications/guidelines that could serve, if appropriate provisions are implemented, as a vehicle to consider life-cycle concepts in design practice

and FEMA are considered as the pertinent codes/standards/specifications/guidelines that could serve, if appropriate provisions will be implemented, as a vehicle to consider life-cycle concepts in design practice.

Conclusions

This paper provided a brief overview of the main results of a survey on life-cycle performance of civil structures and infrastructure systems, with emphasis on life-cycle concepts and methods, deterioration and damage evaluation, life-cycle performance indicators, inspection and maintenance procedures, life-cycle cost analysis, and implementation in design practice. The results of the survey indicate a significant gap between research advances and applicative implementation in this field because (1) there are no specific regulations and (2) life-cycle concepts and methods are still not very well understood in engineering practice. This is related to several shortcomings of current life-cycle approaches in all sectors of civil engineering, including lack of scientific background; lack of detailed life-cycle practices; use of oversimplified and/or inaccurate procedures; use of deterministic approaches; lack of quantitative measures for some deterioration effects; lack of data for numerical calibration and validation; unclear procedures to get data from inspections for assessment; lack of information and uncertainties in costs; no consideration about user, environmental, and end-of-life costs; lack of multidisciplinary and multicriteria approaches; and lack of risk/sustainability metrics to support life-cycle approaches.

There is awareness that a robust prediction of the time-variant structural performance must rely on a reliable and efficient probabilistic deterioration modeling of materials and system components. Advanced models are well established for some of the most detrimental damage processes, such as corrosion and fatigue, and are rapidly becoming available for a wider spectrum of deterioration mechanisms. However, deterioration models are generally very sensitive to change of the probabilistic parameters of the input random variables, and their robust validation and accurate calibration are difficult tasks to be performed because of the limited availability of data. Further efforts in this direction, aimed at gathering new data from both existing structures and experimental tests, are crucial for a successful implementation in practice of life-cycle methods. In this context, inspection and monitoring activities could provide a powerful aid to reduce the level of epistemic uncertainty and to improve the accuracy of predictive probabilistic models.

The availability of structural design codes, standards, and specifications incorporating life-cycle concepts and addressing life-cycle methods and procedures is hence extremely important and represents an important target to be accomplished for the successful implementation in practice of a modern and rational approach to life-cycle analysis of civil engineering structures and infrastructure systems. ASCE 7, AASHTO, Eurocodes, and FEMA are considered as the pertinent codes/standards/specifications/guidelines that would serve as vehicles to implement life-cycle concepts in design practice. Moreover, advances in the standardization of the life-cycle design procedures should be complemented with an increasing awareness of the society, political system, industries, and owners. This is crucial to promote the application of life-cycle concepts in design practice, influence the development of structural design codes and standards, and enhance the state of the civil structures and infrastructures to protect the public safety and improve the quality of life.

Appendix. Survey Questions

1. Type of structure and infrastructure systems of your interest. Please select at most five options:
   Buildings; Bridges; Offshore structures; Power plants; Hydraulic structures; Roads and highways; Railways; Lifelines and power distribution systems; Ports and waterways; Water/wastewater utilities; Pipelines; Other (specify)
2. Name of your organization.
3. Your job role.
4. Number of employees working for your organization.
   <50; 50–250; 251–500; 501–1,000; >1,000
5. Sector of your current organization
   Public sector; Private sector
6. Level of your organization in the public sector (if applicable).
   Federal; State; Regional; Local; Other (specify)
7. Main purpose of your organization.
   Education; Research; Consulting; Other (specify)
8. Do you wish your identity and organization information to remain anonymous in the final report?
9. Please indicate which hazards typically affect the civil engineering structures and infrastructures of your interest. Please select at most five options:
   Overloading; Fatigue or cycle loading; Aging; Environmental/chemical deterioration; Earthquakes; Wind/Tornadoes; Hurricanes; Waves/Tsunamis; Impact; Blast/Explosions; Fire; Ice; Floods; Earth pressure; Equipment malfunctioning; Human errors; Other (specify)

10. Please rank the three most critical hazards affecting the service life of the systems of your concern and explain why these are the most important from a life-cycle perspective.
11. Rate the importance from 1 to 5 of life-cycle concepts in your organization.
12. Would you use the same life-cycle criteria for design of new systems and evaluation of existing systems?
13. Please indicate the design life used in your organization for the civil engineering systems of your concern.
14. Please explain how you estimate the remaining service life for existing systems.
15. Please describe how engineers should evaluate the current state of component/system deterioration.
16. Which tools and methods should engineers use to analyze structural performance and identify damage and possible failure modes? Please select at most three options:

    Engineering experience; Simplified code methods; Linear static/dynamic analysis; Nonlinear static/dynamic analysis; Numerical methods and finite-element analysis; Reliability analysis methods; Probabilistic simulation methods; Other (specify)
17. Which source of damage and deterioration of materials and system components should be considered and properly modeled in life-cycle analysis? Check all that apply.

    Aging; Fatigue; Corrosion; Chloride penetration and carbonation; Sulfate attack; Alkali–Silica reaction; Frost attack; Erosion; Other (specify)
18. Please describe how engineers should evaluate the damage rate of deterioration of materials and components.
19. Please indicate how life-cycle structural performance should be measured.
20. Which are the time-variant system performance indicators that should be considered in life-cycle analysis? Check all that apply.

    Safety; Serviceability; Reliability; Redundancy; Robustness; Resilience; Sustainability; Other (specify)
21. Please rank the three most important system performance indicators for life-cycle design of NEW systems.
22. Please rank the three most important system performance indicators for life-cycle assessment of EXISTING systems.
23. Please indicate which tools and methods can be used to relate structural damage and life-cycle structural performance.
24. Do you consider appropriate and necessary a multihazard approach to life-cycle analysis?
25. In your work, do you implement probabilistic performance measures and numerical simulation methods (e.g., Monte Carlo simulation or similar) in life-cycle analysis?
26. Do you think a probabilistic approach should be incorporated in life-cycle analysis?
27. Please indicate which of the following activities are usually considered and applied with regular frequency in your organization. Check all that apply.

    Evaluation/Rating; Inspection; Maintenance/Repair; Other (specify)
28. For each of the activities indicated above, please specify the frequency (in months).
29. Please describe how engineers should account for routine inspection and maintenance.
30. Please indicate the best approach to coordinate maintenance activities among different infrastructure agencies.
31. Please indicate which life-cycle cost components are generally considered in your sector.

    Direct (e.g., cost to plan, design, and build the system); Indirect (e.g. owner's cost, user's cost, or environmental impact); Both
32. Please list all items that you currently include in quantifying the initial cost.
33. Please list the three most important components of the initial cost.
34. Please list any items that should be considered and that are not currently included in the initial cost estimation.
35. Please list all items that you currently include in quantifying the in-service life-cycle cost.
36. Please list any items that should be considered and that are not currently included in the quantification of the in-service life-cycle cost estimation.
37. In the quantification of the life-cycle cost, do you include the end-of-life removal and replacement costs?
38. In a few words, provide your overall assessment of the current life-cycle practices adopted in your sector. How are these practices implemented?
39. What are the shortcomings of current life-cycle practices implemented in your sector?
40. What are your recommendations to improve current procedures for implementing life-cycle analysis?
41. What is the best way to promote the incorporation life-cycle analysis in design practice? Please select at most three options:

    Design codes and standards; Design guidelines; Social and political awareness; Industry awareness; Owners' awareness; Other (specify)
42. Please indicate tools, models, and/or resources used in your organization for life-cycle analysis. Check all that apply.

    Guidelines provided by owner; Guidelines provided by code; Guidelines outlined by companies or agencies abroad; Engineering judgment; Probabilistic methods; Other (specify)
43. Please rank the tools, models, and resources that you consider particularly useful in life-cycle design and assessment and provide a brief explanation of why these are the most crucial.
44. Are there any official guidelines to regulate the implementation of life-cycle criteria and methods in your sector?
45. Please list any relevant codes, standards, specifications, or design guidelines used by your organization.
46. Please indicate any adjustments that could be made to improve clarity, effectiveness, or thoroughness of the guidelines currently used within your organization for life-cycle analysis.
47. Please list any shortcomings in the documentation/guidelines that are currently utilized within your organization regarding life-cycle analysis.
48. Please indicate pertinent codes/standards/specifications/guidelines that would serve as a vehicle to implement life-cycle concepts in design practice (e.g., ASCE 7, AASHTO, FEMA, Eurocodes).

Acknowledgments

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