Maintenance and Safety of Aging Infrastructure

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Maintenance and Safety of Aging Infrastructure

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Colophon

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Editorial

Welcome to the Book Series *Structures and Infrastructures.*

Our knowledge to model, analyze, design, maintain, manage and predict the life-cycle performance of structures and infrastructures is continually growing. However, the complexity of these systems continues to increase and an integrated approach is necessary to understand the effect of technological, environmental, economical, social and political interactions on the life-cycle performance of engineering structures and infrastructures. In order to accomplish this, methods have to be developed to systematically analyze structure and infrastructure systems, and models have to be formulated for evaluating and comparing the risks and benefits associated with various alternatives. We must maximize the life-cycle benefits of these systems to serve the needs of our society by selecting the best balance of the safety, economy and sustainability requirements despite imperfect information and knowledge.

In recognition of the need for such methods and models, the aim of this Book Series is to present research, developments, and applications written by experts on the most advanced technologies for analyzing, predicting and optimizing the performance of structures and infrastructures such as buildings, bridges, dams, underground construction, offshore platforms, pipelines, naval vessels, ocean structures, nuclear power plants, and also airplanes, aerospace and automotive structures.

The scope of this Book Series covers the entire spectrum of structures and infrastructures. Thus it includes, but is not restricted to, mathematical modeling, computer and experimental methods, practical applications in the areas of assessment and evaluation, construction and design for durability, decision making, deterioration modeling and aging, failure analysis, field testing, structural health monitoring, financial planning, inspection and diagnostics, life-cycle analysis and prediction, loads, maintenance strategies, management systems, nondestructive testing, optimization of maintenance and management, specifications and codes, structural safety and reliability, system analysis, time-dependent performance, rehabilitation, repair, replacement, reliability and risk management, service life prediction, strengthening and whole life costing.

This Book Series is intended for an audience of researchers, practitioners, and students world-wide with a background in civil, aerospace, mechanical, marine and automotive engineering, as well as people working in infrastructure maintenance, monitoring, management and cost analysis of structures and infrastructures. Some volumes are monographs defining the current state of the art and/or practice in the field, and some are textbooks to be used in undergraduate (mostly seniors), graduate and postgraduate courses. This Book Series is affiliated to *Structure and Infrastructure Engineering* (http://www.informaworld.com/sie), an international peer-reviewed journal which is included in the Science Citation Index.

It is now up to you, authors, editors, and readers, to make *Structures and Infrastructures* a success.

Dan M. Frangopol
Book Series Editor

About the Book Series Editor

Dr. Dan M. Frangopol is the first holder of the Fazlur R. Khan Endowed Chair of Structural Engineering and Architecture at Lehigh University, Bethlehem, Pennsylvania, USA, and a Professor in the Department of Civil and Environmental Engineering at Lehigh University. He is also an Emeritus Professor of Civil Engineering at the University of Colorado at Boulder, USA, where he taught for more than two decades (1983–2006). Before joining the University of Colorado, he worked for four years (1979–1983) in structural design with A. Lipski Consulting Engineers in Brussels, Belgium. In 1976, he received his doctorate in Applied Sciences from the University of Liège, Belgium, and holds three honorary doctorates (Doctor Honoris Causa) from the Technical University of Civil Engineering in Bucharest, Romania, the University of Liège, Belgium, and the Gheorghe Asachi Technical University of Iași, Romania.

Dr. Frangopol is an Honorary Professor at seven universities (Hong Kong Polytechnic, Tongji, Southeast, Tianjin, Dalian, Chang'an and Harbin Institute of Technology), and a Visiting Chair Professor at the National Taiwan University of Science and Technology. He is a Distinguished Member of the American Society of Civil Engineers (ASCE), Inaugural Fellow of both the Structural Engineering Institute and the Engineering Mechanics Institute of ASCE, Fellow of the American Concrete Institute (ACI), Fellow of the International Association for Bridge and Structural Engineering (IABSE), and Fellow of the International Society for Health Monitoring of Intelligent Infrastructures (ISHMII). He is also an Honorary Member of the Romanian Academy of Technical Sciences, President of the International Association for Bridge Maintenance and Safety (IABMAS), Honorary Member of the Portuguese Association for Bridge Maintenance and Safety (IABMAS-Portugal Group), Honorary Member of the IABMAS-China Group, and Honorary President of both IABMAS-Italy and IABMAS-Brazil Groups.

Dr. Frangopol is the initiator and organizer of the Fazlur R. Khan Distinguished Lecture Series (http://www.lehigh.edu/frkseries) at Lehigh University. He is an experienced researcher and consultant to industry and government agencies, both nationally and abroad. His main research interests are in the application of probabilistic concepts and methods to civil and marine engineering, including structural reliability, probability-based design and optimization of buildings, bridges and naval ships, structural health monitoring, life-cycle performance maintenance and management of structures and infrastructures under uncertainty, risk-based assessment and decision making, infrastructure sustainability and resilience to disasters, stochastic mechanics and earthquake engineering.

According to ASCE (2010) "Dan M. Frangopol is a preeminent authority in bridge safety and maintenance management, structural systems reliability, and life-cycle civil engineering. His contributions have defined much of the practice around design specifications, management methods, and optimization approaches. From the maintenance of deteriorated structures and the development of system redundancy factors to assessing the performance of long-span structures, Dr. Frangopol's research has not only saved time and money, but very likely also saved lives."

Dr. Frangopol's work has been funded by NSF, FHWA, NASA, ONR, WES, AFOSR, ARDEC and by numerous other agencies. He is the Founding President of the International Association for Bridge Maintenance and Safety (IABMAS, www.iabmas.org) and of the International Association for Life-Cycle Civil Engineering (IALCCE, www.ialcce.org), and Past Director of the Consortium on Advanced Life-Cycle Engineering for Sustainable Civil Environments (COALESCE). He is also the Vice-President of the International Association for Structural Safety and Reliability (IASSAR, www.columbia.edu/cu/civileng/iassar), the former Vice-President of the International Society for Health Monitoring of Intelligent Infrastructures (ISHMII, www.ishmii.org), and the founder and current chair of the ASCE Technical Council on Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems (http://content.seinstitute.org/committees/strucsafety.html).

Dr. Frangopol is the recipient of several prestigious awards including the 2014 ASCE James R. Croes Medal, the 2012 IALCCE Fazlur R. Khan Life-Cycle Civil Engineering Medal, the 2012 ASCE Arthur M. Wellington Prize, the 2012 IABMAS Senior Research Prize, the 2008 IALCCE Senior Award, the 2007 ASCE Ernest Howard Award, the 2006 IABSE OPAC Award, the 2006 Elsevier Munro Prize, the 2006 T. Y. Lin Medal, the 2005 ASCE Nathan M. Newmark Medal, the 2004 Kajima Research Award, the 2003 ASCE Moisseiff Award, the 2002 JSPS Fellowship Award for Research in Japan, the 2001 ASCE J. James R. Croes Medal, the 2001 IASSAR Research Prize, the 1998 and 2004 ASCE State-of-the-Art of Civil Engineering Award, and the 1996 Distinguished Probabilistic Methods Educator Award of the Society of Automotive Engineers (SAE). Among several awards he has received at the University of Colorado, Frangopol is the recipient of the 2004 Boulder Faculty Assembly Excellence in Research Scholarly and Creative Work Award, the 1999 College of Engineering and Applied Science's Research Award, the 2003 Clarence L. Eckel Faculty Prize for Excellence, and the 1987 Teaching Award. He is also the recipient of the Lehigh University's 2013 Eleanor and Joseph F. Libsch Research Award. He has given plenary keynote lectures in numerous major conferences held in Asia, Australia, Europe, North America, South America, and Africa.

Dr. Frangopol is the Founding Editor-in-Chief of *Structure and Infrastructure Engineering* (Taylor & Francis, www.informaworld.com/sie), an international peer reviewed journal. This journal is dedicated to recent advances in maintenance, management, and life-cycle performance of a wide range of structures and infrastructures. He is the author or co-author of two books, 38 book chapters, more than 300 articles in referred journals, and over 500 papers in conference proceedings. He is also the editor or co-editor of 40 books published by ASCE, Balkema, CIMNE, CRC Press, Elsevier, McGraw-Hill, Taylor & Francis, and Thomas Telford, and an editorial board member of several international journals. Additionally, he has chaired and organized several national and international structural engineering conferences and workshops.

Dr. Frangopol has supervised 37 Ph.D. and 54 M.Sc. students. Many of his former students are professors at major universities in the United States, Asia, Europe, and South America, and several are prominent in professional practice and research laboratories.

For additional information on Dr. Frangopol's activities, please visit http://www.lehigh.edu/~dmf206/

Preface

The purpose of this book is to present the latest research findings in the field of *maintenance and safety of aging infrastructure*. For this purpose, the aim was to attract state-of-the-art papers that deal with the use of advanced computational and/or experimental techniques in damage and vulnerability assessment as well as maintenance and retrofitting of aging structures and infrastructures (e.g., buildings, bridges, lifelines, and naval ships). A deteriorating infrastructure leads to increased functioning costs and reduced safety and can lead to a catastrophic failure with devastating environmental, social and economic consequences. In contrast, well-maintained civil infrastructure can substantially increase a country's competitiveness in a global economy and enhance resilience to adverse circumstances such as natural hazards (e.g., earthquakes, hurricanes and floods) and man-made disasters (e.g., vehicular collision and blasts due to terrorists' attacks).

Cost-efficient maintenance and management of civil infrastructure systems requires balanced consideration of both the system performance and the total cost accrued over their entire life-cycle. Another major problem is that the performance of structural systems is usually reduced during its functioning due to aging, environmental stressors, and other factors. Thus, current structural condition state is usually assessed by visual inspection or more advanced automatic structural health monitoring techniques. Furthermore, maintenance managers often require a list of prioritized maintenance interventions for civil infrastructure on an annual and/or long-term basis. Various unavoidable uncertainties associated with both randomness (i.e., aleatory uncertainty) and imperfect knowledge (i.e., epistemic uncertainty) also play a crucial role in maintenance and management of engineering systems. Taking into account the aforementioned issues, this volume aims to present the recent developments of life-cycle maintenance and management planning for deteriorating civil infrastructure considering simultaneously the present thinking as well as the latest research findings in this area. This volume is a book of high-quality and self-contained chapters, which present the state-of-the-art theoretical advances and applications in various areas of *maintenance and safety of aging infrastructure*. This edited book consists of selected contributions of experts in the aforementioned field.

In this context, major topics treated in this book include: risk assessment, redundancy, robustness, management, safety, reliability, optimization, structural health monitoring, life-cycle performance, extreme events, hazards, dynamic assessment, retrofitting, bridge networks, fatigue life, stochastic control, decision making, bridges, marine structures, dams, pavements, aging structures, uncertainties, NDT methods, damage assessment, climate change, climate adaptation, sustainability, hazard mitigation, inspection, maintenance and repair, as briefly described below. Due to the multidisciplinary nature and complexity of the topics and the applications covered in the chapters of this volume they are not categorized, but instead they are placed in alphabetic order (based on first author's last name).

In the first chapter, M. Akiyama, D.M. Frangopol and H. Matsuzaki present fundamental issues related to reliability-based durability and service life assessment of reinforced concrete (RC) structures in a marine environment, where a major problem is the chloride-induced corrosion of reinforcing bars. As it is explained for new RC structures, the concrete quality and concrete cover to prevent the chloride-induced reinforcement corrosion causing the deterioration of structural performance during whole lifetime of RC structures should be determined. For this purpose, a simple design criterion with durability design factors that satisfy the target reliability level is presented. On the other hand, for evaluating the service life of existing structures, it is necessary to consider the effect of the chloride-induced reinforcement corrosion on the deterioration of structural capacity and stiffness. Hence, to evaluate the capacity and stiffness of deteriorated structures, spatial variability associated with the steel weight loss over the entire components needs to be considered using X-ray photography and digital image processing. It is concluded that based on service life reliability assessment of existing RC structures by incorporating spatial variations, the optimal temporal and spatial intervals of inspection could be determined.

S. Alampalli advocates that bridge inspections and maintenance are essential to assure safety, increase durability, reduce life-cycle costs, maintain mobility, and improve reliability of transportation networks. The chapter focuses on bridges in the United States, which are usually examined using visual methods by bridge inspectors, manually assessing the condition of various elements. These inspections form a basis for maintenance and other repair actions that are needed to improve durability and maintain the required service level. Therefore, inspection and maintenance issues should be considered by engineers to ensure that all components can be accessed and evaluated by inspection and maintenance personnel, so that appropriate maintenance and repairs can be performed in a cost-effective and timely fashion. This will assure long-term durability, while not significantly affecting the level of service and mobility. These issues are presented herein based on the established practice, experience, norms and guidelines among bridge designers and inspectors as well as maintenance engineers in the United States.

The chapter by A. Alipour and B. Shafei deals with structural vulnerability measures for the assessment of deteriorating bridges in seismic prone areas. For this purpose, the authors propose a vulnerability index as a time-dependent measure of the seismic damageability of deteriorating bridges. To estimate this index, the life-cycle performance of reinforced concrete highway bridges subjected to earthquake ground motions is evaluated under the assumption that the bridge components are continuously exposed to the attack of chloride ions. Corrosion process of the concrete is simulated through a computational approach that calculates structural degradation over the entire service life of the structural components. The structural capacity and seismic response of corroded bridges is investigated and seismic fragility curves are generated for the deteriorating bridges using updated parameters. The time-dependent fragility curves are employed to predict the vulnerability index, which combines the effects of expected seismic events and chloride-induced corrosion. This index can be used for the structural design and performance assessment of bridges as well as for the life-cycle cost analysis of bridges subjected to multiple natural hazards and environmental stressors.

The design of complex structural systems requires an accurate definition of the project requirements and a detailed verification of the expected performance. Structural condition knowledge that can be gained by structural health monitoring is the topic of the contribution by S. Arangio and F. Bontempi. In this context, it is stressed that structural health monitoring (SHM) plays an essential role to improve the knowledge level for a complex structural system and to allow reliable evaluations of the structural safety in operational conditions. SHM should be planned from the design phase and carried out during the entire life-cycle, since it represents an effective way to control the structural system in a proactive way. By using SHM the circumstances that may eventually lead to deterioration, damage and unsafe operations can be diagnosed and mitigated in a timely manner, thus, costly replacements can be avoided or delayed. In order to deal with the large quantity of data gathered from the continuous monitoring various techniques exist. In this work, different approaches are discussed and applied to illustrate how SHM can lead to two levels of design knowledge gain: locally, on the specific structure, and more globally, on the general class of similar structures.

Safety analysis and maintenance scheduling of critical infrastructure become increasingly complicated due to uncertainties and complexity, which result significantly from aging and from interactive phenomena. In the chapter by M. Beer, I.A. Kougioumtzoglou and E. Patelli established and emerging concepts and techniques for efficient and realistic uncertainty quantification are discussed. In this regard, emphasis was put on engineering applications, and in particular, on challenges associated with civil engineering structures and infrastructure to verify and ensure their safety. For this purpose, the main two challenges discussed are: (a) the realistic and reliable quantification of uncertainties prevalent in civil engineering complex systems, and (b) the efficient numerical analysis of such complex systems in the presence of uncertainties. Emerging concepts and approaches which address these challenges are presented.

The aim of the chapter by F. Biondini and D.M. Frangopol is to present the latest research findings in the field of structural robustness and progressive collapse of deteriorating structural systems, with emphasis on the relationship among structural robustness, static indeterminacy, structural redundancy, and failure times. Damage is viewed as a progressive deterioration of the material properties and its amount is evaluated at the member level by means of a damage index associated with prescribed patterns of cross-sectional deterioration. An index of structural integrity is also defined to quantify the severity of the structural failure with respect to its consequences. The role of damage propagation on structural robustness is investigated by considering different propagation mechanisms and by using a damage-sensitive fault-tree analysis. The elapsed time between local failure and structural collapse is also investigated as an indicator of the ability of the system to be repaired after local failure. The methodology is implemented on a reinforced concrete frame under different corrosion damage scenarios.

E. Brühwiler introduces a novel approach to verify the fatigue safety of existing bridges using monitored data in an explicit way and to predict their future service life. A methodology to exploit data from long-term monitoring for gaining meaningful information is presented. The approach is illustrated by its application to real bridges in Switzerland. It is shown that there are no 'old' bridges, but bridges that provide adequate performance or not. Therefore, extending the service life of bridges by following the approach presented herein allows for continuous utilization of existing structures rather than their replacement which introduces a novel meaning to the notion of "lifecycle" of civil structures. Hence, this approach is clearly in agreement with the principles of sustainable development.

Management and safety of existing concrete structures via optical fiber distributed sensing is investigated by J.R. Casas, S. Villalba and V. Villalba. More specifically, the use of Optical Backscatter Reflectometer (OBR) as a distributed fiber optic system to measure strain and detect cracking in concrete structures is examined. A laboratory test as well as two real structures (a bridge and a cooling tower of a power plant) were used to investigate the effectiveness of the OBR sensors when applied to complex and large-scale structural systems. The presented results show the feasibility of this technique despite of the roughness of the concrete surface and the heterogeneity due to the presence of aggregates of different sizes. All applications verify that OBR sensors are capable of detecting cracks that are hardly visible. Crucial factors are the good preparation of the concrete surface as well as the adoption of the correct bonding agent, while extra care is necessary whenever continuous fiber has curvature changes. Regarding cost, it is pointed out that the deployment of the OBR monitoring system in real-world infrastructure is more economical compared to equivalent monitoring techniques.

The chapter by Á. Cunha, E. Caetano, F. Magalhães and C. Moutinho describes in a concise and systematic manner the most important issues related to the dynamic testing and continuous monitoring of large-scale civil infrastructure. For this purpose, an extensive discussion of modern perspectives concerning testing techniques, instrumentation, modal identification, vibration serviceability safety checking and damage detection is presented. Special attention is given on the efficient implementation of Operational Modal Analysis (OMA) and its application for tracking the evolution of modal parameters in long-term dynamic monitoring applications. In addition, it is also illustrated that statistical methods can be used to remove the influence of environmental and operational factors (e.g., temperature, intensity of traffic, wind) on the modal variability, supporting the development of reliable techniques for vibration based damage detection. Moreover, it is demonstrated that continuous dynamic monitoring can also be used for safety checking of vibration serviceability limits as well as for better understanding wind induced effects on the modal properties or the structural response of large-scale structures.

D. De Leon-Escobedo, D.J. Delgado-Hernandez and J.C. Arteaga-Arcos advocate in their contribution that the balanced implementation of strategies to design and maintain facilities must consider the risk management as a tool to measure the economical effectiveness of alternatives and to allocate limited resources effectively. Under this perspective, the approaches presented are based on the expected life-cycle cost analysis and Bayesian networks, the first of which is applied to the case of a bridge and an offshore oil platform, and the latter to an earth dam in Mexico. The impact of cost/benefit ratios, epistemic uncertainties and the relative importance of contributing factors are weighted and used as a decision making tool for a risk-based planning of resources allocation for maintenance of structures with different revenues/cost ratios.

Risk-based maintenance of aging ship structures is the focus of the study by Y. Garbatov and C. Guedes Soares. Their chapter reviews recently developed mathematical tools for risk-based assessment of marine structures subjected to the degrading effect of corrosion. It discusses the methods for corrosion deterioration modeling and presents a formulation for the reliability assessment and risk-based maintenance planning of corroded marine structures taking into account different maintenance strategies. Furthermore, it is noted that inspection planning reveals that the application of repair cost optimization for floating structures involves many uncertainties. Classical theory of system maintenance that describes the failure of components by Weibull probabilistic models, which represent failure rates in operational phases and in the aging phases of the life of components are used.

As illustrated in the work of K. Kaito, K. Kobayashi and K. Obama, the deterioration of pavement is a complex phenomenon in which the deterioration process of road surface and the decline in load bearing capacity of the entire pavement occur concurrently. In pavement management, it is important to comprehensively assess the deterioration state of the pavement structure and determine desirable repair policies. In this study, the authors propose a methodology for discussing a pavement repair policy for a target road span by (a) extracting intensive management spans through the relative evaluation of road surfaces based on the results of road condition surveys, and (ii) estimating the load bearing capacity through the falling weight deflectometer (FWD) survey targeted at intensive management spans. For this purpose, the mixed Markov deterioration hazard model is applied to national road in Japan, and intensive management spans are selected by comparing heterogeneity parameters. A FWD survey is conducted and load bearing capacity is measured for the selected intensive management spans and some of sound road spans, and the authors empirically verify the appropriateness of the proposed method of extracting intensive management spans through the comparison of heterogeneity parameters.

S. Lavrenz, J. Murillo Hoyos and S. Labi illustrate the importance of assessing the effectiveness of alternative infrastructure preservation interventions, typically, in terms of a measure of effectiveness (MOE) which is in turn expressed in the form of a performance indicator (PI). It is important to perform such quantifications as part of ex post evaluations (i.e., after the intervention) or in ex ante assessments of infrastructure intervention projects (i.e., before the decision is made either to proceed with an intervention or to identify the optimal choice from multiple alternative interventions). This would facilitate the development of explicit, objective, and consistent decisions based on all relevant and quantifiable cost or benefits associated with the intervention. For this purpose, this chapter presents MOEs that include increase in performance (the extent to which the performance indicator (PI) is enhanced over the remaining life of the infrastructure), the service life (the time or accumulated loadings for the PI to reach a pre-specified threshold), and the area bounded by the performance function (a reflection of the time period over which good performance is sustained, representing both the average performance and the intervention service life), probability of infrastructure survival until a certain time, and the probability that some distress of a certain extent or severity is encountered. Field data from in-service infrastructure are used to demonstrate the use of these mathematical constructs.

The chapter by Y. Li, M.G. Stewart and S. Bjarnadottir presents a risk-based framework to assess the hurricane damage risks of power distribution (utility) poles, investigate the cost-effectiveness of different mitigation strategies, and evaluate adaptation strategies under potential climate change. The losses due to power outrage and the high replacement costs of aging poles requires a detailed investigation into the cost effectiveness of various mitigation strategies, which may reduce replacement costs and damage risks. The framework includes a reliability analysis of the power distribution poles using fragility analysis considering various sources of uncertainties, the effects of degradation of timber poles, probabilistic wind models, a life-cycle cost (LCC) benefit analysis for economical viability of various mitigation strategies, and an assessment of the potential impacts of climate change on annual failure probability of power distribution poles. Climate change is found to have a significant impact on the annual failure probability of the distribution poles when they are subjected to changing patterns of hurricane hazard. Under this perspective, the economic viability of adaptation strategies to replace or strengthen power distribution poles in coastal areas under various climate change scenarios is evaluated.

As it is explained in the contribution of A. Medury and S. Madanat, transportation infrastructure management refers to the process of allocating a limited set of resources to a system of deteriorating facilities (roads, bridges, tunnels, etc) for maintenance, rehabilitation and replacement (MR&R) activities. Typically, the objective is to minimize the total costs incurred by the agency over a given planning horizon, while providing adequate recognition to the performance of individual facilities, as well as the costs incurred by the users. In order to model the decision-making problem, which involves the optimization of decisions over multiple stages, Markov decision processes (MDP) are widely used, especially in the context of incorporating uncertainty in the underlying facility performance models. In this regard, state-of-the-art Markov decision process (MDP)-based approaches in infrastructure management are presented. Furthermore, this work seeks to explore the suitability of approximate dynamic programming (ADP) methods to incorporate network-induced dynamics into system-level MR&R decision-making. An efficient ADP framework is proposed to incorporate structural and economic interdependence into network-level MR&R decision-making, while parametric studies are conducted to infer the impact of network-based constraints on the decision-making process.

The impact of corrosion into the safety of structures in marine environments is the objective of the chapter by R.E. Melchers. More specifically, corrosion and pitting of structural steel used in marine pipelines and for off-shore mooring chain are important factors in continued integrity and service performance and are best considered in a reliability framework. Recent new studies have shown that corrosion and pitting are complex nonlinear functions of exposure period and of various environmental influences, including that of marine microorganisms. This has considerable implications on the way structural safety assessments using structural reliability theory can be performed. This aspect is reviewed for steel plates, sheet piling, steel pipelines and for mooring chains as used in the offshore oil industry. An example is given for the assessment of the probability of failure through severe pitting observed in some cases for mooring chains. The new corrosion theory implies that for maximum pit depth the Frechet distribution rather than the usual Gumbel distribution is more appropriate for reliability analysis. The reasons for this outcome and the various implications are discussed.

Important techno-economic issues related to reliable and efficient retrofitting and refurbishment of existing road bridges are discussed by C. Modena, G. Tecchio, C. Pellegrino, F. da Porto, M.A. Zanini and M. Donà. It is evident that suitable interventions are essential for lengthening bridges' structural life and delaying their complete substitution, the "downtime" costs, all generally very difficult to manage by network authorities. The design of retrofit process requires a complex comprehensive approach, which starts with the assessment of the current state and the definition of the condition value of the bridge by inspections, identification tests, structural analyses, etc. On this basis, the definition of the proper interventions in terms of both material and implementation techniques is then carried out. The application of such methodologies to different road bridge types (masonry, reinforced concrete, steel) is described, while usual restoration and retrofitting techniques for all these different bridge types are briefly presented. In the sequence, significant case studies of rehabilitation interventions are presented. These retrofitting and refurbishment interventions outline a methodological approach, taking into account the typological characteristics of the structure, the state of maintenance, the functional requirements and the environmental aspects connected to the employed repair and strengthening of each structural system.

K.G. Papakonstantinou and M. Shinozuka discuss stochastic control approaches for structural maintenance. In general, huge investments are needed in order to substantially improve the current infrastructure conditions, which are rarely, if ever, fully available in practice. To address effectively this urgent societal need for safe structures and infrastructure systems under limited resources, science-based management of assets is needed. Stochastic control methods and Bayesian principles have a long, successful history of implementation in risk management and minimum life-cycle costing of civil engineering structures. In this work, a practical framework for decision-making, under a variety of uncertainties, concerning the management of deteriorating civil structures is presented based on Markov Decision Processes (MDP) that answers the critical questions of where, when and what type of inspection and repair should be performed, in order for a structure to maintain an acceptable safety level at the minimum possible cost. This enables decision-makers to plan an optimum life-cycle policy to perform effective inspection and maintenance actions. Utilizing a realistic example, the proposed method is compared with state-of-the-art methodologies to verify its theoretical and practical supremacy.

Modeling inspection uncertainties for on-site condition assessment using non-destructive testing (NDT) tools is discussed in the work of F. Schoefs. Maintenance of existing aging infrastructures lies generally on condition assessment based-from the most easily used to the most intrusive ones- on visual inspection, non-NDT and structural health monitoring (SHM) with embedded sensors. For some applications, the condition assessment can be considered as perfect and the aging model parameters are updated using Bayesian techniques for instance. When considering aging infrastructures this is generally not the case due to: (a) the size of the structure is large and the inspection should be carried out on a limited number of positions; (b) the budget devoted to inspection is subtracted from the global amount of money available to plan the Inspection-Maintenance and Repair schedule (IMR). Thus, the most efficient and inexpensive condition assessment schemes should be selected. That leads decision-makers to consider: (i) partial, and (ii) non-perfect tools in the decision scheme. The objective of this chapter related to (i) is: to present deficiencies of classical discrete inspection approaches, to describe the current methodologies for inspection optimisation, and to present an efficient approach based on polynomial chaos to minimize the error of measurement. Furthermore, the goals of this chapter with respect to (ii) are: to present in a general format the modelling of imperfections, emphasizing on the role of the exact definition of the employed protocol, as well as the chain of uncertainties from calibration tests and results in laboratory to on-site assessment including various factors (i.e., human, environmental,) that affect the assessment. Furthermore, to analyse how these basic quantities can be introduced as parameters in a rational aid-tool for the optimisation of resources allocation by minimizing the total cost along the service life.

The motivation of the study by M.-K. Söderqvist is to examine the impact of condition description and inspection data quality in infrastructure management. It is emphasized that a well-organized inspection system is the key element of a successful engineering structure management. Actually, it forms the basis and is an integral part of the whole management system. The system assessment results are as reliable as the data in the database. Hence, the experience of the engineers and the use of the management system have shown that the available condition and damage data must continuously be improved and completed. The importance of inspection training and other quality improving methods, their impact on bridge maintenance, repair and rehabilitation (MR&R) as well as bridge aging modeling are discussed. MR&R preservation and functionality goals for bridges and other engineering structures are presented to better describe the whole management process of fund allocation. Well qualified inspection and well-chosen condition indicators provide a valuable and necessary assistance to reach the targets of the maintenance operations policy.

The topic of the contribution of M.G. Stewart, D.V. Val, E. Bastidas-Arteaga, A. O'Connor and X. Wang climate adaptation engineering and risk-based design and management of infrastructure, with emphasis on increases in economic (loss) risks expected for existing infrastructure subject to climate-induced changes. This work aims at exploiting the impact of climate change on infrastructure performance and to pave the way for more efficient and resilient infrastructure, and help 'future proof' existing infrastructure to a changing climate. The performance of existing infrastructure may degrade if subject to more extreme natural hazards or accelerated degradation of material properties. This chapter describes how risk-based approaches are well suited to optimising climate adaptation strategies related to the design and maintenance of existing infrastructure. Such approaches may include retrofitting or strengthening of existing structures, or enhanced designs. Risk-based decision support is described to assess the risks and economic viability of climate adaptation measures, especially on the aspect of life-cycle costs during their service, which includes embodied and operating energy costs. Furthermore, stochastic methods are used to model infrastructure performance, effectiveness of adaptation strategies, exposure, and costs. The latest research findings related to climate adaptation strategies are provided for various complex engineering applications.

Large-scale transportation networks comprise structures of various size and complexity, requiring different strategies for management and maintenance. Under this perspective, the work of B. Yanev focuses on comparing bridge condition evaluations with life-cycle expenditures in an illustrative manner. More specifically, the objective of this chapter is to review the condition assessments of the New York City bridge network and the known expenditures for rehabilitation, repair and maintenance over a period exceeding two decades. The evaluations include condition ratings generated by visual biennial inspections, as well as reports of potential hazards and other assessments. In contrast with uncertain forecasting models, this work directly compares the bridge condition database with the magnitude of the remedial measures. Given the uncertain correlation between evaluations and actual conditions on one hand, and the vague effectiveness of remedial actions on the other, a rigorous relationship cannot be established even in retrospect. Nevertheless, comparing a huge amount of real data from bridge and element condition ratings with network level expenditures reveals a functional relationship between the project level structural demand and the supply of remedial actions. Hence, important guidelines are provided based on the accumulated experience of the presented bridge network and it is concluded that preventive maintenance and preservation emerge as preferable, both in terms of direct and user costs, especially for larger infrastructure.

In the last chapter, the principles of redundancy-based design of non-deterministic systems are presented by B. Zhu and D.M. Frangopol. The motivation of this study is to propose an efficient redundancy factor to provide a rational reliability-based design of components in structural systems. The definition of this redundancy factor is properly illustrated via a characteristic example. By using idealized systems consisting of identical components, the effects of system models, correlations among the resistances of components, number of components in the system, mean value of the load, and coefficients of variation of load and resistances on the redundancy factor are investigated. For the representative case where the coefficients of variation of resistance and load are set to be the commonly used values, the redundancy factors of N-component systems associated with different correlation cases and system models are evaluated. Two types of limit states are provided, in which system redundancy is taken into account from the load and resistance side, respectively. Finally, a highway bridge example is presented to demonstrate the application of the proposed redundancy factor to real-life engineering problems.

The aforementioned collection of chapters provides an overview of the present thinking and state-of-the-art developments into the field of *maintenance and safety of aging infrastructure*. The book is targeted primarily to researchers, students and engineers that are active in this field. It is hoped that the collection of these chapters in a single book will be found useful for both academics and practicing engineers.

The book editors would like to express their deep gratitude to all authors for their time and effort devoted to the completion of their contributions for this volume. Furthermore, we are most appreciative to the reviewers for their effective comments that helped authors to substantially strengthen their work. Finally, the editors would like to thank the personnel of CRC Press / Balkema, especially Mr. Alistair Bright and Mr. Richard Gundel, for their kind cooperation and support for the publication of this book.

Dan M. Frangopol
Yiannis Tsompanakis
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Dr. Frangopol is an experienced researcher and consultant to industry and government agencies, both nationally and abroad. His work has been funded by NSF, FHWA, ONR, NASA, WES, AFOSR, ARDEC and by numerous other agencies.

Dr. Frangopol holds three honorary doctorates from Belgium and Romania. He is an Honorary Professor at seven universities (Hong Kong Polytechnic, Tongji, Southeast, Tianjin, Chang'an, Dalian, and Harbin Institute of Technology). For his contributions, Dr. Frangopol has been recognized with several prestigious awards, including the T. Y. Lin Medal, Newmark Medal, Khan Life-Cycle Civil Engineering Medal, Croes Medal (twice), Howard Award, Wellington Prize and Moisseiff Award, to name only a few.

Dr. Frangopol is devoted to serving the profession, having held various leadership positions in national and international organizations. He is the Founding President of the International Association for Bridge Maintenance and Safety (IABMAS) and of the International Association for Life Cycle Civil Engineering (IALCCE), and the Vice-President of the International Association for the Structural Safety and Reliability (IASSAR). He is also the Founding Chair of the ASCE-SEI Technical Council on life-cycle performance, safety, reliability and risk of structural systems and of the IASSAR Technical Committee on life-cycle performance, cost and optimization. He is a member of the Board of Governors of the Engineering Mechanics Institute (EMI) of the ASCE, Past-Chair of the Technical Activities Division of the 20,000+ members of the Structural Engineering Institute (SEI) of the ASCE, and Past Vice-President of the International Society for Structural Health Monitoring of Intelligent Infrastructure

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Dr. Tsompanakis has excellent leadership, interpersonal and negotiating skills and many international cooperations with other scientific groups and engineering firms in Greece and abroad (USA, UK, Italy, Germany, France, Serbia, Spain, etc.). He is highly skilled in implementation and management of quantitative/qualitative state-of-the-art research. He has significant practical and scientific experience from his participation in many national and international projects (structures, geostructures, lifelines, etc.), working either with his group or jointly with other collaborating teams. He has also served in many administrative positions at the Technical University of Crete.

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