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Bridge Maintenance, Safety and Management: Techniques and Challenges

桥梁维护、安全与运营管理
——技术与挑战

陈艾荣 阮欣 编

人民交通出版社
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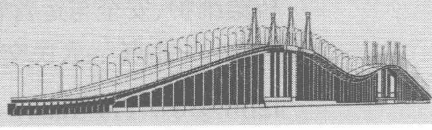

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内容提要

桥梁的维护、安全与运营管理工作日益受到重视，本书涵盖了桥梁安全与维护基础理论和方法、大型桥梁的管理方法与策略、桥梁病害机理分析与整治、桥梁监测与控制等方面的最新工程与研究实践。本书在2012年召开的第一届全国桥梁维护与安全学术会议主题报告的基础上，精选了九篇论文后经原作者拓展后形成，每个章节均全面、系统、深入地阐述了该领域中的热点问题。

本书可供从事桥梁设计、施工、管理及相关研究人员参考，也可供高等院校相关专业的研究生和高年级本科生参考使用。

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序

改革开放以来，我国交通基础设施建设突飞猛进，取得了举世瞩目的成绩。特别是在桥梁工程方面，建成了数量惊人的各类桥梁，并且完成了一批突破世界纪录的特大桥梁。在总结经验和成绩的同时，桥梁界同仁也深深感觉到，提高桥梁的运营保障和安全水平，大力发展在役桥梁的管理、维护技术是桥梁工程界正在迎接的挑战。

国际桥梁维护与安全协会（International Association for Bridge Maintenance and Safety, IABMAS, http://www.iabmas.org）成立于1999年，是一个致力于提升桥梁养护、安全和管理水平的国际性学术组织。该协会的宗旨为提升桥梁养护、安全和管理领域的国际交流与合作，增强理论与实践之间的沟通，促进技术发展和创新。自协会创建以来，通过主办和协办国际会议、技术论坛等活动，为桥梁管养相关领域的工程师、管理者和研究人员提供了一个相互了解和交流的平台，对促进领域发展做出了积极贡献。

2002年7月，由IABMAS组织召开的第一届桥梁维护、安全和管理国际会议（1st International Conference on Bridge Maintenance, Safety and Management）在西班牙巴塞罗那成功举行。此后，第二至第六届会议分别于2004年10月在日本京都、2006年7月在葡萄牙波尔图、2008年7月在韩国首尔、2010年7月在美国费城、2012年7月在意大利斯特雷萨召开。这一系列会议得到了各国日益密切的关注和积极的响应，与会人数逐年增多，第六届会议与会人数近800人。

为提升国内桥梁管养领域的学术联系，促进相关领域的工程师、管理者

和研究人员的学术交流，促进国际交流，建立一个国际性的交流平台，由同济大学陈艾荣教授提议，经国际桥梁维护与安全协会同意，2012 年 4 月，在同济大学成立了国际桥梁维护与安全协会中国团组（IABMAS - China Group），并同期举办了第一届全国桥梁维护与安全学术会议。

来自全国的 160 名代表参加了本届会议，来自同济大学、东南大学、湖南大学、长安大学、中交公路规划设计院有限公司等单位的 10 名代表进行了主题发言，国际桥梁维护与安全协会主席 Dan Frangopol 教授专程到会祝贺并发言。本书以这次会议主题发言为基础，经作者修改完善后形成。全书共 9 个章节，涵盖了桥梁维护与管理方面的基础研究、技术开发、应用集成等方面，内容涉及大型桥梁的系统管理、中小跨径桥梁病害治理、桥梁检测与评估技术、桥梁管理系统与数字化等，代表了我国目前这一领域的发展现状。Frangopol 也特别为本书编写了一个章节，介绍基于可靠性的基础设施全寿命管养理论的基本框架和最新进展。

安全与维护问题将是未来几年桥梁工程领域研究的重点和热点。根据中国团组会议的决定，中国团组会议将每逢单数年份召开，第二届会议将于 2013 年 4 月由重庆交通大学承办。2014 年，将在上海举办第七届桥梁维护、安全和管理国际会议（IABMAS 2014）。

本书是中国团组出版的系列图书的第一部，今后将陆续推出，希望以这样一种形式向国内业界同仁介绍最新的研究成果。借此机会，也感谢对中国团组和第一届国内会议提供支持的单位和专家。

由于时间、水平有限，难免错漏，望广大读者不吝赐教。

编者

2012 年 12 月

目录

第 1 章 Integrated Reliability-based Life-cycle Framework for Maintenance, Rehabilitation and Management of Aging Civil and Marine Infrastructures

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Reliability-based life-cycle management techniques allow for the effective management of deteriorating structures which can, simultaneously, account for satisfactory performance thresholds, total expected life-cycle cost, and fast restoration of the proper functionality of the structural system after an extreme event. Such techniques are only applicable through a well-constructed framework which integrates different safety, financial, and environmental aspects to achieve the management goals. Uncertainties associated with various aspects of the life-cycle are considered in this framework. While multiple performance measures can be utilized within this framework, system reliability concepts provide a rational indicator of the system performance and safety. The primary objective of this keynote paper is to highlight the recent accomplishments in the life-cycle performance assessment, maintenance, monitoring, rehabilitation, management and optimization of aging structural systems under uncertainty based on reliability. Applications of the developed integrated framework to life-cycle management of individual bridges, bridge networks and naval ships are presented.

1.1 Introduction

Time-dependent structural deterioration processes such as corrosion, fatigue, and increase in demand (e. g., increase in traffic volume) impose continuous aging effects on infrastructure systems. These effects, individually or when combined with those arising from extreme events such as earthquakes and hurricanes, can cause catastrophic consequences. Time-dependent deterioration significantly alters the resistance of the structure and reduces the initial structural load carrying capacity (Tsompanakis 2010). Accordingly, the life-cycle of the infrastructures should be clearly analyzed and studied taking into consideration different aging effects, environmental stressors, and man-made and natural hazards.

The complexity of this type of analysis may increase due to the presence of various aleatory and epistemic uncertainties associated with structural damage occurrence and propagation, as well as, the damage detection processes. These uncertainties should be considered in the life-cycle analysis through an integrated life-cycle framework for the maintenance and management of the aging infrastructures. In this framework, different possible deteriorating mechanisms are studied in order to predict the time-dependent performance and damage evolution profiles. These profiles are next used to perform multi-objective optimization considering the possible damaging mechanisms and their possible outcomes. The outputs of this optimization process are the best management actions, such as maintenance and inspection times, which yield an affordable life-cycle cost and satisfactory safety and service life of the structure. Information from the structural health monitoring (SHM) provides a solid foundation to reduce the uncertainties associated with prediction of resistance and demand of the structure (Frangopol and

Messervey 2009, Okasha and Frangopol 2009). Considering these uncertainties, reliability-based techniques serve as a rational solution to evaluate the safety levels of structural systems while considering various sources of randomness. Accordingly, reliability-based techniques played a great role in the probabilistic life-cycle management of structures (Frangopol and Neves 2004, Okasha and Frangopol 2012).

This keynote paper highlights the recent accomplishments in the life-cycle performance assessment, maintenance, monitoring, rehabilitation, management and optimization of aging structural systems under uncertainty based on reliability. Different applications of this framework are also presented.

1.2 Performance assessment of structures

Reliability-based methods for performance assessment of structures offer the best means for treating various uncertainties. Additionally, these methods provide a rational way to assess the overall structural safety other than the commonly employed methods to design and evaluate structural systems based on component analysis (Frangopol and Nakib 1991). In the next subsections, the main reliability concepts for components and structural systems are presented.

1.2.1 Structural reliability analysis

In general, the reliability of a structural component can be related to the probability of failure, defined as the probability of violating a certain limit state $g(X) = 0$. The performance function $g(X)$ is defined as

$$g(X) = R - S \tag{1.1}$$

where R and S are, respectively, the random capacity and demand of the structure, and X is the random variable vector. Based on the defined limit state function, the probability of failure P_f can be defined as

$$P_f = P(g(X) \leqslant 0) \tag{1.2}$$

The probability density functions (PDFs) of R, S, and $g(X)$ as well as the probability of failure P_f are represented in Figure 1.1. Thus, the reliability index β can then be defined as

$$\beta = \Phi^{-1}(1 - P_f) \tag{1.3}$$

where $\Phi^{-1}(\cdot)$ denotes the inverse standard normal cumulative distribution function (CDF).

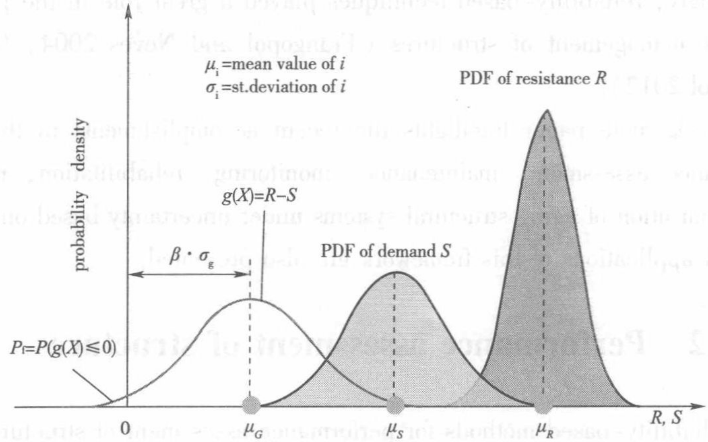

Figure 1.1 Schematic showing probability of failure concepts

For cases where R and S are statistically independent normally or lognormally distributed random variables, exact expressions for calculating the probability of failure can be formulated (see for example Ditlevsen and Madsen 2007). For more complex problems, where R and S follow a probability density function (PDF) other than normal or lognormal, efficient reliability techniques can be used to evaluate the component reliability, such as the first order method (FORM), second order method (SORM), and Monte Carlo simulation. The FORM and SORM have been widely employed in many structural reliability problems and various software packages, such as RELSYS (Estes and Frangopol 1998), to calculate the reliability indices of structural components and systems.

1.2.2 System reliability concepts

System-based reliability concepts can be thought as an extension of the component reliability or single failure mode evaluation to cover multiple components or failure modes of the system under consideration. In these methods, complex interactions within the system are taken into account to evaluate the overall system performance. Different system configurations such as the series, parallel, or series-parallel system interactions, shown in Figure 1.2, can be considered.

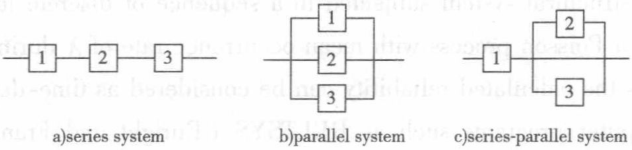

Figure 1.2 Different system configurations

For this type of analysis, regardless of the system configuration, the system reliability is expressed in terms of the component reliabilities. For a series system, in which the failure of any component will lead to the system failure, the system probability of failure is defined as

$$P_{\mathrm{fsys}} = P_{\mathrm{f}}(g_1 \leqslant 0 \cup g_2 \leqslant 0 \cup \cdots \cup g_n \leqslant 0) \tag{1.4}$$

where g_n represents the performance function of the nth component. On the other hand, for a parallel system, in which the system failure occurs with the failure of all components, the system failure probability is defined as

$$P_{\mathrm{fsys}} = P_{\mathrm{f}}(g_1 \leqslant 0 \cap g_2 \leqslant 0 \cap \cdots \cap g_n \leqslant 0) \tag{1.5}$$

Similarly, the system probability of failure for different series-parallel configurations can be formulated. For more complex systems, different methods such as the cut- set method can be used to represent the system performance (Hoyland and Rausand 1994).

1.2.3 System reliability in a life-cycle context

For life- cycle analysis, the evolution of the damage levels and accordingly component and system reliabilities is required to be evaluated. Thus the component limit state is defined as

$$g(X,t) = R(t) - S(t) = 0 \tag{1.6}$$

and the instantaneous probability of failure is defined as (Ellingwood 2005)

$$P_{\mathrm{f}}(t) = \int_0^{\infty} F_R(x,t) f_S(x,t)\,\mathrm{d}x \tag{1.7}$$

where $F_R(x,t)$ is the instantaneous CDF of the resistance and $f_S(x,t)$ is the instantaneous PDF of the load effects at time t.

Measures for the reliability of systems over a given period of time has been defined by researchers such as the time-dependent reliability indicator defined by Mori and Ellingwood (1993). This performance indicator gives the probability of survival of a structural system subjected to a sequence of discrete loading events described by a Poisson process with mean occurrence rate of λ during a period of time t_L. Thus the calculated reliability can be considered as time-dependent reliability. Computer programs such as RELTSYS (Enright and Frangopol 2000) were developed to quantify the reliability of general series-parallel systems by using the reliability function proposed by Mori and Ellingwood (1993). Lifetime functions (Leemis 1995) can also be used to evaluate the time-dependent reliability and have been utilized for the life-cycle performance prediction of bridge structures (Yang, Frangopol, and Neves 2004, Okasha and Frangopol 2010b, 2010c, 2010d).

1.3 Life-cycle optimization

After evaluating the structural performance and based on the severity of the deterioration, decisions regarding the repair or strengthening of the managed structural systems have to be made. However, due to the large number of these deteriorating structures, funds are usually not available to meet all the maintenance and repair needs. On the other hand, it is known that in some cases, the cost of maintaining the infrastructures might be more than the cost of building new ones (Miyamoto, Kawamura, and Nakamura 2000). Therefore, the reduction of maintenance costs is a challenge that must be addressed in the integrated maintenance management framework. The proper allocation of the available maintenance and management budgets can be done through the life-cycle optimization process.

For service life extension, maintenance interventions are scheduled to either delay the occurrence of reaching a performance indicator to its threshold or improve the state of the performance indicator if its threshold is reached. Thus, maintenance types may be categorized into two general groups: preventive (PM) and essential (EM) (Kong and Frangopol 2003). PM actions are usually time-based, that is, they are applied at pre-specified time instants over the life-cycle of the structure. In contrast, EM actions are performance-based in that they are applied when some performance indicators reach pre-defined target values. The effect of both maintenance types on the performance profile of a structure is shown in Figure 1.3.

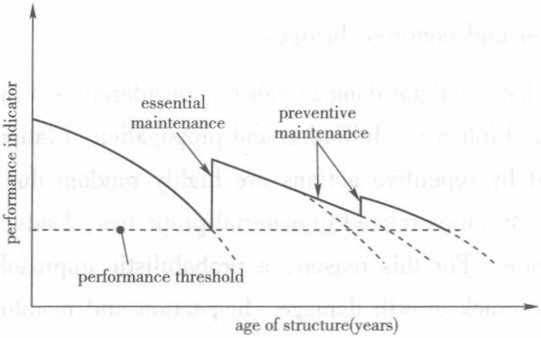

Figure 1.3 Effect of different maintenance types on the performance of the structure

Optimization is the essential tool for providing best decision support in the life-cycle management framework. Components of this framework rely on this computationally intensive process to find the best solution fulfilling the objectives and satisfying the predefined constraints. This describes optimization as the core of infrastructures management process. All elements of this process interact and sometimes conflict, calling for the use of multi-criteria optimization that can extract the best solution among conflicting elements (Frangopol 2011). Different objectives for the life-cycle optimization have been included in recent research work such as, extending the service life of the structure, minimizing damage detection delay, and minimizing the life-cycle cost, among others. Moreover, different conflicting objectives can also be considered simultaneously yielding a Pareto-optimal solution set. Frangopol and Okasha (2009) performed a comparison between the computational times required in a genetic algorithm (GA) process for maintenance optimization using multiple performance measures. They concluded that the lifetime based reliability is the fastest.

The applications of this management framework covered steel bridges, reinforced concrete (RC) bridges, steel ships, aluminum ships, and networks of structures. For the studied structures, fatigue, corrosion, and earthquake hazards were treated as the major damaging actions. The next section presents an overview of the research work performed by the first author and his current and former students and research associates to address these damaging actions on these types of structures.

1.3.1 Steel and concrete bridges

For steel bridges, fatigue damage can be considered as a main threat for the structural safety and integrity. Initiation and propagation of fatigue cracks in steel structures induced by repetitive actions are highly random due to both aleatory and epistemic uncertainties related to material properties, loads, damage, modeling and other factors. For this reason, a probabilistic approach is necessary to predict the fatigue crack growth damage. Inspection and monitoring planning for steel bridges subjected to fatigue has been performed in Kim and Frangopol (2011a, 2011e). Kim and Frangopol (2011a) presented a probabilistic approach for combined inspection/monitoring planning for fatigue-sensitive structures considering uncertainties associated with fatigue crack initiation, propagation and damage detection. This combined inspection/monitoring planning is the solution of an optimization formulation, where the objective is minimizing the expected damage detection delay. Furthermore, this formulation was extended to a bi-criterion optimization considering the conflicting relation between expected damage detection delay and cost. A set of Pareto solutions was obtained by solving this bi-criterion optimization problem. From this set, a solution can be selected balancing, in an optimum manner, inspection and monitoring times, quality of inspections, monitoring duration, and number of inspections and monitorings. The proposed approach was applied to the Yellow Mill Pond Bridge located in Bridgeport, Connecticut, USA.

SHM is an effective tool to determine the condition state of bridges and to reduce epistemic uncertainties affecting the performance deterioration process (Kim and Frangopol 2010). Continuous monitoring is needed to reliably assess and predict the performance of bridges. However, due to limited financial resources, continuous monitoring is not practical. Therefore, a cost-effective SHM strategy is necessary. Kim and Frangopol (2011e) presented such an approach in which the probability that the performance prediction model, based on monitoring data, is usable in the future is computed by using the statistics of extremes and availability theory. This probability represents the availability of the monitoring data over non-monitoring periods. The monitoring cost and availability can be found by solving a bi-objective optimization problem. This problem consists of simultaneously minimizing the total monitoring cost and maximizing the availability of the monitoring data for performance prediction. Pareto solutions associated with monitoring duration and prediction duration were obtained. The proposed approach was applied to an existing bridge located in Wisconsin, USA.

Kwon and Frangopol (2010) used SHM data to perform fatigue assessment for steel bridges. They focused on evaluating the PDFs of equivalent stress range based on field monitoring data. The AASHTO Guidelines (AASHTO 2002) were used to estimate capacity of structural details in the fatigue reliability assessment, whereas long-term monitoring data was used to provide efficient information for fatigue in terms of equivalent stress range and cumulative number of stress cycles. The approach used probabilistic distributions associated with stress ranges to effectively predict equivalent stress ranges for bridge fatigue reliability assessment. The fatigue detail coefficient, A, and the equivalent stress range, S_{re}, were both treated as random variables in the proposed fatigue reliability approach. This approach was illustrated on two existing bridges which are expected to experience finite or infinite fatigue life.

Kwon and Frangopol (2011) focused on conducting lifetime performance assessment and management of aging steel bridges under fatigue by integrating three prediction models: fatigue reliability model, crack growth model, and probability of detection model. Their approach used these models for planning interventions on fatigue-sensitive structures. Based on information from field monitoring and/or non-destructive evaluation, prediction models were developed to (a) estimate the time-dependent fatigue performance using fatigue reliability model, (b) provide the time-dependent crack growth using crack growth model, and (c) quantify the detection capability associated with fatigue cracks using probability of detection model. In order to assess and manage bridge fatigue life, the three models were combined based on two parameters (i.e., number of cycles and crack size). This combined approach was used for