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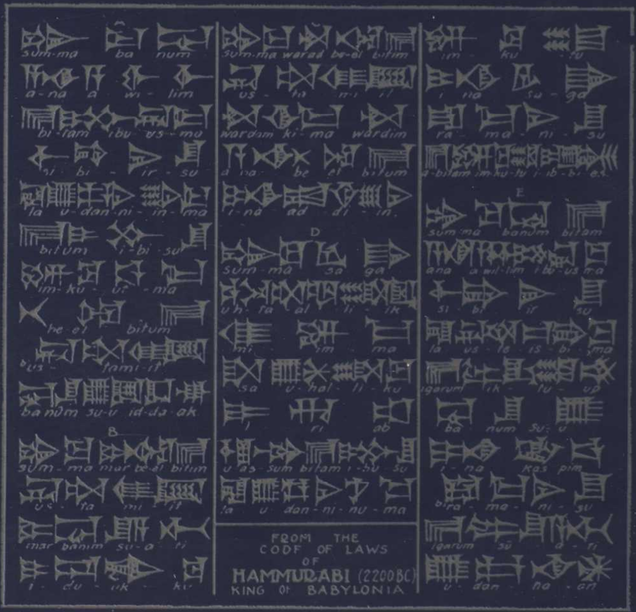
Reliability Of Structures

结构可靠度

[美] Andrzej S. Nowak Kevin R. Collins 著

张 川导读



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序

本书为读者提供了结构可靠度分析的实用工具，可以作为有结构工程或结构力学背景的高年级本科生或研究生的教材。

许多可靠度方面的书籍都是为研究者而写的，通常从数学或理论的角度切入。本书则将重点放在结构可靠度理论的实际应用上。在简明给出基本概念、原理以及公式的基础上，采用大量的实例来加以应用说明。本书不仅可作为学生的参考书，对于工程师也同样会有帮助，通过将可靠度作为结构设计的一个重要方面而拓宽工程师们的视野。本书对专业人员了解设计规范的发展背景，确定更可靠的设计方法及优化方案，以及合理评价既有结构的安全性等均具有重要的参考价值。

本书第1章介绍了结构可靠度分析的基本内容。讨论了结构可靠度研究的目的，以及结构设计中固有的不确定性的来源。第2章简要综述了可靠度和统计学的基本理论。重点放在可靠度分析方法所需的定义和公式方面。然后对在结构可靠度应用中常用的概率分布进行了综述，并对贝叶斯方法进行了简单讨论。第3章讨论了随机变量函数。描述了诸如协方差、相关系数以及相关矩阵等概念及定义。第4章给出了能解决结构可靠度问题的一些模拟方法。重点放在蒙特卡洛模拟方法上。第5章中定义了极限状态和极限状态方程。可靠度和失效概率被认为是荷载与抗力的函数。在此基础上给出了可靠度分析方法，得到了简单的二阶矩平均值公式。第6章给出了荷载模型。考虑的荷载分量有：建筑物和桥梁的恒载、活载以及环境荷载（如风、雪、地震）等。还给出了可靠度分析中荷载组合的方法。第7章讨论了抗力模型。给出了钢梁、柱子、受拉杆件以及节点的统计参数，考虑了组合截面和非组合截面。对钢筋混凝土杆件和预应力杆件，给出了受弯承载力和受剪承载力的参数。第8章给出了发展基于可靠度的设计规范的方法。给出了确定荷载与抗力系数的基本步骤以及标定方法。第9章讨论了系统可靠度问题。对于串联系统、并联系统以及混合系统给出了实用的公式。评价了结构杆件的相关性对系统可靠度的影响。第10章综述了结构设计和施工中的人为误差模型。根据发生机制、原因以及后果对误差进行了分类。讨论了误差调查的结果，并提出了处理误差的方法，重点讨论了灵敏性分析，给出了典型构件的灵敏性函数。

本文作者 Andrzej S. Nowak 是美国密执安大学土木与环境工程系教授，是美国土木工程师学会（ASCE）和美国混凝土学会（ACI）的资深会员，是结构可靠度领域国际著名学者。曾经担任 ASCE 结构安全性和可靠度委员会主席，ACI348 结构安全性委员会主席等重要学术职务。他在结构可靠度领域的研究，为美国高速公路与桥梁规范（LRFD ASSHTO）、安大略高速公路与桥梁规范等新一代以概率论为基础的设计规范的发展奠定了基础。

利用书末的教师反馈表，教师可以向麦格劳-希尔教育出版公司申请相关的教学课件和资料。

张　川

2005年2月

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ANDRZEJ S. NOWAK is a professor of civil and environmental engineering at the University of Michigan. He received his M. S. (1970) and Ph. D. (1975) from Politechnika Warszawska in Poland. Prior to joining the faculty at the University of Michigan in 1979, he worked at the University of Waterloo in Canada (1976–1978) and the State University of New York in Buffalo (1978–1979). Professor Nowak's research has led to the development of a probabilistic basis for the new generation of design codes for highway bridges, including load and resistance factors for the LRFD AASHTO Code and the Ontario Highway Bridge Design Code, and fatigue evaluation criteria for BS-5400 (United Kingdom). He has authored or coauthored over 250 publications, including books, journal papers, and articles in conference proceedings.

Professor Nowak is also an active member of national and international professional organizations. He chairs TRB Committee A2C00 on Structures, ASCE Committee on Structural Safety and Reliability, IABSE WC 1 on Structural Performance, Safety and Analysis, and IFIP WG 7.5 on Reliability and Optimization of Structural Systems. He is a past chair of ACI Committee 348 on Structural Safety, and TRB Committee A2C05 on Dynamics and Field Testing of Bridges. He is a Fellow of ASCE, Fellow of ACI, Honorary Professor of Politechnika Warszawska, and a recipient of the ASCE Moisseiff Award for the paper entitled "Calibration of LRFD Bridge Code."

KEVIN R. COLLINS is an assistant professor of civil and environmental engineering at the University of Michigan. He received his bachelor of civil engineering (BCE) degree from the University of Delaware in May 1988, his master of science (MS) degree from Virginia Polytechnic Institute and State University in December 1989 and his doctor of philosophy (Ph. D.) degree from the University of Illinois in October 1995. Between his M. S. and Ph. D. degrees he worked for MPR Associates, Inc., in Washington, D. C., for 2 1/2 years. Dr. Collins' research interests are in the areas of earthquake engineering, structural dynamics, and structural reliability.

Dr. Collins is an associate member of the American Society of Civil Engineers (ASCE), a member of the Earthquake Engineering Research Institute (EERI), a member of the American Society for Engineering Education (ASEE), an affiliate member of the Seismological Society of America (SSA), and an affiliate member of the Structural Engineers Association of Michigan (SEAMi). He belongs to the honor societies of Chi Epsilon, Tau Beta Pi, and Phi Kappa Phi.

PREFACE

THE OBJECTIVE OF this book is to provide the reader with a practical tool for reliability analysis of structures. The material is intended to serve as a textbook for a one-semester course for undergraduate seniors or graduate students with a background in structural engineering and structural mechanics. Previous exposure to probability and statistics is helpful but not required; the most important aspects of probability and statistics are reviewed early in the text.

Many books on reliability are written for researchers, often approaching the subject from a mathematical and theoretical perspective. The focus of this book is on practical applications of structural reliability theory. The basic concepts, interpretations, and equations are presented, and their use is then demonstrated in examples. The book should be helpful to both students and practicing structural engineers and should broaden their perspective by considering reliability as an important dimension of structural design. In particular, the methodology discussed here is applicable in the development of design codes, the development of more reliable designs, optimization, and the rational evaluation of existing structures.

ORGANIZATION OF THE BOOK

Chapter 1 introduces structural reliability analysis. The objectives of the study of reliability of structures and the sources of uncertainty inherent in structural design are discussed.

Chapter 2 briefly reviews the theory of probability and statistics. The emphasis is placed on the definitions and formulas needed for derivation of reliability analysis procedures. The random variable is defined and its parameters, such as the mean, median, standard deviation, coefficient of variation, cumulative distribution function, probability density function, and probability mass function, are considered. The probability distributions commonly used in structural reliability applications are reviewed; these include the normal, lognormal, extreme types I, II, and III, uniform, Poisson, and gamma distributions. A brief discussion of Bayesian methods is also included.

In Chapter 3, functions of random variables are considered. Concepts and parameters such as covariance, coefficient of correlation, and covariance matrix are described. Formulas are derived for parameters of a function of random variables. Special cases considered in this chapter are the sum of uncorrelated normal random variables and the product of uncorrelated lognormal random variables.

Chapter 4 presents some simulation techniques that can be used to solve structural reliability problems. The Monte Carlo simulation technique is the focus of this chapter. Two other methods are also discussed: the Latin hypercube sampling method and Rosenblueth's point estimate method.

The concepts of limit states and limit state functions are defined in Chapter 5. Reliability and probability of failure are considered as functions of load and resistance. The fundamental structural reliability problem is formulated. The reliability analysis methods are also presented in Chapter 5. The simple second-moment mean value formulas are derived. Then, the Hasofer-Lind reliability index is defined. An iterative procedure is shown for variables with full distributions available.

Load models are presented in Chapter 6. The considered load components include dead load, live load for buildings and bridges, and environmental loads (such as wind, snow, and earthquake). Some techniques for combining loads together in reliability analyses are also presented.

Resistance models are discussed in Chapter 7. Statistical parameters are presented for steel beams, columns, tension members, and connections. Noncomposite and composite sections are considered. For reinforced concrete members and prestressed concrete members, the parameters are given for flexural capacity and shear. The results are based on the available test data and simulations.

The development of a reliability-based design code is outlined in Chapter 8. The basic steps for finding load and resistance factors and a calibration procedure used in several recent research projects are presented.

Chapter 9 deals with the important topic of system reliability. Useful formulas are presented for a series system, a parallel system, and mixed systems. The effect of correlation between structural components on the reliability of a system is evaluated. The approach to system reliability analysis is demonstrated using simple practical examples.

Models of human error in structural design and construction are reviewed in Chapter 10. Errors are classified with regard to mechanism of occurrence, cause, and consequences. Error survey results are discussed. A strategy to deal with errors is considered. Special focus is placed on the sensitivity analysis. Sensitivity functions are presented for typical structural components.

ACKNOWLEDGMENTS

Work on this book required frequent discussions and consultation with many experts in theoretical and practical aspects of structural reliability. Therefore, we would like to acknowledge the support and inspiration we received over many years from our colleagues and teachers, in particular Niels C. Lind, Palle Thoft-Christensen, Dan M. Frangopol, Mircea D. Grigoriu, Rudiger Rackwitz, Giuliano Augusti, Robert Melchers, Michel Ghosn, Fred Moses, James T. P. Yao, Ted V. Galambos, M. K. Ravindra, Brent W. Hall, Robert Sexsmith, Yozo Fujino, Hitoshi Furuta, Gerhard Schueller, Y. K. Wen, Wilson Tang, Alfredo Ang, C. Allin Cornell, Bruce Ellingwood, Janusz Murzewski, John M. Kulicki, Dennis Mertz, Jozef Kwiatkowski, and Tadeusz Nawrot.

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Finally, we would like to thank our wives, Jolanta and Karen, for their patience and support.

Andrzej S. Nowak
Kevin R. Collins

CONTENTS

1

INTRODUCTION

1.1 OVERVIEW

Many sources of uncertainty are inherent in structural design. Despite what we often think, the parameters of the loading and the load-carrying capacities of structural members are not deterministic quantities (i. e., quantities which are perfectly known). They are random variables, and thus absolute safety (or zero probability of failure) cannot be achieved. Consequently, structures must be designed to serve their function with a finite probability of failure.

To illustrate the distinction between deterministic and random quantities, consider the loads imposed on a bridge by car and truck traffic. The load on the bridge at any time depends on many factors, such as the number of vehicles on the bridge and the weights of the vehicles. As we all know from daily experience, cars and trucks come in many shapes and sizes. Furthermore, the number of vehicles that pass over a bridge fluctuates, depending on the time of day. Since we don't know the specific details about each vehicle that passes over the bridge or the number of vehicles on the bridge at any time, there is some uncertainty about the total load on the bridge. Hence the load is a random variable.

Society expects buildings and bridges to be designed with a reasonable safety level. In practice, these expectations are achieved by following code requirements specifying design values for minimum strength, maximum allowable deflection, and so on. Code requirements have evolved to include design criteria that take into account some of the sources of uncertainty in design. Such criteria are often referred to as *reliability-based design criteria*. The objective of this book is to provide the background needed to understand how these criteria were developed and to provide a basic tool for structural engineers interested in applying this new approach to other situations.

The reliability of a structure is its ability to fulfill its design purpose for some specified design lifetime. Reliability is often understood to equal the probability that a structure will not fail to perform its intended function. The term "failure" does not necessarily mean catastrophic failure but is used to indicate that the structure does not perform as desired.

1.2 OBJECTIVES OF THE BOOK

This book attempts to answer the following questions:

How can we measure the safety of structures? Safety can be measured in terms of reliability or the probability of uninterrupted operation. The complement to reliability is the probability of failure. As we discuss in later chapters, it is often convenient to measure safety in terms of a reliability index instead of probability.

How safe is safe enough? As mentioned earlier, it is impossible to have an absolutely safe structure. Every structure has a certain nonzero probability of failure. Conceptually, we can design the structure to reduce the probability of failure, but increasing the safety (or reducing the probability of failure) beyond a certain optimum level is not always economical. This optimum safety level has to be determined.

How does a designer implement the optimum safety level? Once the optimum safety level is determined, appropriate design provisions must be established so that structures will be designed accordingly. Implementation of the target reliability can be accomplished through the development of probability-based design codes.

1.3 POSSIBLE APPLICATIONS

Structural reliability concepts can be applied to the design of new structures and the evaluation of existing ones. A new generation of design codes is based on probabilistic models of loads and resistances. Examples include the American Institute of Steel Construction Load and Resistance Factor Design (LRFD) code for steel buildings (AISC, 1986, 1994), Ontario Highway Bridge Design Code for bridges (OHBDC, 1979, 1983, 1991), American Association of State Highway and Transportation Officials LRFD code (AASHTO, 1994, 1998), Canadian Highway Bridge Design Code (1998), and many European codes (e.g., CEC, 1984).① In general, reliability-based design codes are efficient because they make it easier to achieve either of the following goals:

- For a given cost, design a more reliable structure.
- For a given reliability, design a more economical structure.

The reliability of a structure can be considered as a rational evaluation criterion. It provides a good basis for decisions about repair, rehabilitation, or replacement. A structure can be condemned when the nominal value of load exceeds the nominal load-carrying capacity. But in most cases a structure is a system of components, and failure of one component does not necessarily mean failure of the structural system. When a component reaches its ultimate capacity, it may continue to resist the load while loads are redistributed to other components. System reliability provides a methodology to establish the relationship between the reliability of an element and the reliability of the system.

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① Many acronyms are used in structural engineering and structural reliability. Appendix A lists acronyms used in this book.

1.4 HISTORICAL PERSPECTIVE

Many of the current approaches to achieving structural safety evolved over many centuries. Even ancient societies attempted to protect the interests of their citizens through regulations. The minimum safety requirements were enforced by specifying severe penalties for builders of structures that did not perform adequately. The earliest known building code was used in Mesopotamia. It was issued by Hammurabi①, the king of Babylonia, who died about 1750 B.C. The "code provisions" were carved in stone, and these stone carvings are preserved in the Louvre in Paris, France. (Figure 1.1 is a picture of this "document.") The responsibilities were defined depending on the consequences of failure. If a building collapsed killing a son of the owner, then the builder's son would be put to death; if the owner's slave was killed, then the builder's slave was executed; and so on.

For centuries, the knowledge of design and construction was passed from one generation of builders to the next. A master builder often tried to copy a successful structure. Heavy stone arches often had a considerable safety reserve. Attempts to increase the height or span were based on intuition. The procedure was essentially trial and error. If a failure occurred, that particular design was abandoned or modified.

As time passed, the laws of nature became better understood; mathematical theories of material and structural behavior evolved, providing a more rational basis for structural design. In turn, these theories furnished the necessary framework in which probabilistic methods could be applied to quantify structural safety and reliability. The first mathematical formulation of the structural safety problem can be attributed to Mayer (1926), Streletzki (1947), and Wierzbicki (1936). They recognized that load and resistance parameters are random variables and therefore, for each structure, there is a finite probability of failure. Their concepts were further developed by Freudenthal in the 1950s (e.g., Freudenthal, 1956). The formulations involved convolution functions that were too difficult to evaluate by hand. The practical applications of reliability analysis were not possible until the pioneering work of Cornell and Lind in the late 1960s and early 1970s. Cornell proposed a second-moment reliability index in 1969. Hasofer and Lind formulated a definition of a format-invariant reliability index in 1974. An efficient numerical procedure was formulated for calculation of the reliability index by Rackwitz and Fiessler (1978). Other important contributions have been made by Ang, Veneziano, Rosenblueth, Esteva, Turkstra, Moses, Grigoriu, Der Kiuregian, Ellingwood, Corotis, Frangopol, Fujino, Furuta, Yao, Brown, Ayyub, Blockley, Stubbs, Mathieu, Melchers, Augusti, Shinozuka, and Wen. By the end of 1970s, the reliability methods reached a degree of maturity, and now they are readily available for applications. They are used primarily in the development of new design codes.

The developed theoretical work has been presented in books by Thoft-Christensen and Baker (1982), Augusti, Barrata, and Casciati (1984), Madsen, Krenk, and Lind (1985), Ang and Tang (1984), Melchers (1987), Thoft-Christensen and Murotsu (1986), and Ayyub and McCuen (1997), to name just a few. Other books available in the area of structural reliability include Murzewski (1989) and Marek, Gustar, and Anagnos (1996).

It is important to note that most reliability-based codes in current use apply reliability concepts to the design of structural members, not structural systems. In the coming years, one can expect a further

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① Hammurabi, Code of 汉谟拉比法典

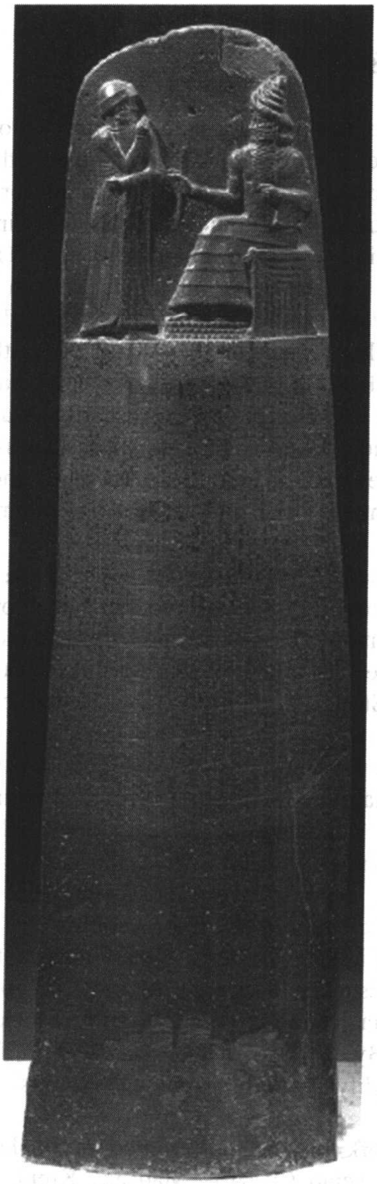

FIGURE 1. 1 The Code of Hammurabi.
The engraved image at the top shows King Hammurabi receiving the Code from the Sun God. The code itself is inscribed on the sides of the stone below the image.
(Photograph reproduced with permission of the Musée du Louvre and the Réunion des Musées Nationaux Agence Photographique.)

acceleration in the development of analytical methods used to model the behavior of structural systems. It is expected that this focus on system behavior will lead to additional applications of reliability theory at the system level.

1.5 UNCERTAINTIES IN THE BUILDING PROCESS

The building process includes planning, design, construction, operation/use, and demolition. All components of the process involve various uncertainties. These uncertainties can be put into two major categories with regard to causes: natural and human.

Natural causes of uncertainty① result from the unpredictability of loads such as wind, earthquake, snow, ice, water pressure, or live load. Another source of uncertainty attributable to natural causes is the mechanical behavior of the materials used to construct the building. For example, material properties of concrete can vary from batch to batch and also within a particular batch.

Human causes include intended and unintended departures from an optimum design. Examples of these uncertainties during the design phase include approximations, calculation errors, communication problems, omissions, lack of knowledge, and greed. Similarly, during the construction phase, uncertainties arise due to the use of inadequate materials, methods of construction, bad connections, or changes without analysis. During operation/use, the structure can be subjected to overloading, inadequate maintenance, misuse, or even an act of sabotage.

Because of these uncertainties, loads and resistances (i. e., load-carrying capacities of structural elements) are random variables. It is convenient to consider a random parameter (load or resistance) as a function of three factors:

Physical variation factor. This factor represents the variation of load and resistance that is inherent in the quantity being considered. Examples include a natural variation of wind pressure, earthquake, live load, and material properties.

Statistical variation factor. This factor represents uncertainty arising from estimating parameters based on a limited sample size. In most situations, the natural variation (physical variation factor) is unknown and it is quantified by examining limited sample data. Therefore, the larger the sample size, the smaller the uncertainty described by the statistical variation factor.

Model variation factor. This factor represents the uncertainty due to simplifying assumptions, unknown boundary conditions, and unknown effects of other variables. It can be considered as a ratio of the actual strength (test result) and strength predicted using the model.

How these three factors come into a reliability analysis is discussed in later chapters.

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① uncertainty 不确定性