清华大学学术专著

Experiment and Calculation of Reinforced Concrete at Elevated Temperatures

钢筋混凝土的高温性能试验及其计算

Zhenhai Guo　Xudong Shi
过镇海　时旭东

Tsinghua University Press
清华大学出版社

清 华 大 学 学 术 专 著

Experiment and Calculation of Reinforced Concrete at Elevated Temperatures

钢筋混凝土的高温性能试验及其计算

Zhenhai Guo   Xudong Shi
过镇海   时旭东

清华大学出版社
北京

内 容 简 介

本书主要论述钢筋混凝土结构及其材料在不同温度-荷载史下的受力性能。通过混凝土和钢筋材料，以及梁、柱和超静定结构试件等的系列高温试验研究讨论了主要结果，分析了一般性规律，建立了材料的耦合热-力本构关系，给出了准确的理论分析和简化的实用计算方法。本书的研究成果可应用于混凝土结构的火灾温度场分析、抗火分析和设计，以及火灾后的损伤评估和事故处理。

本书可用作研究生教材，也可供相关领域研究人员和工程技术人员参考使用。

图书在版编目（CIP）数据

钢筋混凝土的高温性能试验及其计算 = Experiment and Calculation of Reinforced Concrete at Elevated Temperatures：英文 / 过镇海，时旭东编著. --北京：清华大学出版社，2011.11

（清华大学学术专著）

ISBN 978-7-302-26854-3

Ⅰ. ①钢… Ⅱ. ①过… ②时… Ⅲ. ①钢筋混凝土—高温—性能分析—英文 Ⅳ. ①TU528.571

中国版本图书馆 CIP 数据核字(2011)第 188220 号

责任编辑：陈朝晖
责任印制：李红英

出版发行：清华大学出版社　　**地　址**：北京清华大学学研大厦 A 座
http://www.tup.com.cn　　**邮　编**：100084
社 总 机：010-62770175　　**邮　购**：010-62786544
投稿与读者服务：010-62776969，c-service@tup.tsinghua.edu.cn
质 量 反 馈：010-62772015，zhiliang@tup.tsinghua.edu.cn
印 装 者：北京雅昌彩色印刷有限公司
经　销：全国新华书店
开　本：185×230　**印　张**：20.75　**插　页**：1
版　次：2011 年 11 月第 1 版　**印　次**：2011 年 11 月第 1 次印刷
印　数：1～2000
定　价：69.00 元

产品编号：040718-01

PREFACE

Reinforced concrete structures are the most common component in structural engineering. Engineering experience and research achievements, improvements in manufacturing technology, and applications of new and efficient materials have led to a great deal of progress in reinforced concrete structures. The performance index is increasing continuously, structural configurations are more varied, and the scope of applications is expanding greatly. Today, reinforced concrete structures are used widely not only in various civil and public buildings, single- and multi-story industrial buildings, and high-rise and large-span buildings, but also in bridges, communication installations, and hydraulic and underground engineering. Reinforced or prestressed concrete structures are also used in special structures, e.g., TV towers, electrical transmission poles, silos, chimneys, even reactor and containment vessels in nuclear power plants, and very large hydraulic forging presses.

Generally, concrete structures work at room temperature (<60 °C) and they can be designed or their safety can be checked using the current codes.[0-1] However, some structures, e.g., metallurgical and chemical plants, chimneys, nuclear reactors and their containment structures, and hydraulic forging presses, work constantly in high temperature environments (100–500 °C). In addition, building fire accidents occasionally occur due to natural or man-made causes. These accidents cause the structure in a building bearing a high temperature attack to reach maximum temperatures of 1000 °C or higher within a short time (e.g., 1 h). When the concrete structure reaches elevated temperatures, it experiences cracking, increased deformation, and reduced strength, because of serious deterioration of material behavior and internal force redistribution of the structure. Then the structure may fail and even collapse, and this will result in significant economic losses and loss of life.

The research work related to this field is still limited in China and no corresponding design code is available for engineers. Therefore, the development requirements of construction engineering cannot be met, and research on the behavior of concrete materials and structures at elevated temperatures has become an important and urgent task.

The authors and several postgraduates have completed several research projects in this field since 1989. These projects are financially supported by the 863 High Science and Technology Plan of the National Science Committee, National Natural Science Foundation, and Doctoral Research Foundation of the Education Ministry of China. This book is a systematic collection and summary of the experimental and theoretical research results of these projects. The postgraduate students who took part in the projects are: Quiping Shi, Xudong Shi, Yütao Guo, and Jianping Yang (doctoral students) and Wei Li, Li Jiang, Huadong Li, Jianlin Nan, Tongguang Lü, Jieying Zhang, and Jinfeng Sun (masters students). In addition, many undergraduate students took part in the experimental work during their graduation projects.

The behavior of a concrete structure at high temperature is much more complicated than that at room temperature, and its theoretical analysis is quite difficult. When the environmental temperature of a structure is elevated under some conditions, a corresponding dynamic nonuniform temperature field is formed, the strength and deformation behavior of the materials (concrete and reinforcement) deteriorates significantly at high temperatures, and the internal forces undergo severe redistribution. Furthermore, temperature and load (or stress) show an obvious coupling effect, and the constitutive relationships of the materials and the mechanical behavior of the structure vary considerably under various temperature–load paths. Therefore, the mechanical behavior of concrete material, members, and structures is presented first in this book, according to the experimental results in which temperature and load act together. The working mechanisms are analyzed, experimental data are collected, general regularities are deduced, theoretical analyses are developed, and simplified calculation methods are given for engineering applications.

There are four parts in this book, which are introduced separately: the mechanical behavior of concrete and reinforcement at elevated temperatures and the coupling temperature–stress constitutive relationship of concrete; the theoretical analysis and calculation charts and tables for the temperature fields of the member section; the testing method at elevated temperature and behavior regularities of various basic structural members and statically indeterminate structures; and the theoretical analysis along the temperature–load history and practical method of calculating the ultimate strength of the members and structures at elevated temperature, and evaluation criteria and method of grading damage in structures after fire.

This book provides important concepts, experimental data, and the method and parameters of the theoretical analysis for engineers and technicians engaged in research, design, or construction, when they design and calculate the resistance of a structure at high temperature (fire) or deal with an existing structure after a fire accident. Moreover, this book may be used as a textbook for a concrete structure course by university lecturers, postgraduate, and undergraduate students of structural engineering.

The Chinese version of this book was written by two authors. Zhenhai Guo was responsible for Chapters 1, 2, 3, 4, 8, 9, 11, 13 (part), and 14, and Xudong Shi was responsible for Chapters 5, 6, 7, 10, 12, and 13 (part). Zhenhai Guo revised and completed the manuscript. This English version was translated from the Chinese version by Zhenhai Guo.

The authors sincerely thank the organizations that financially supported and assisted with the related projects and publication: 863 High Science and Technology Plan of the National Science Committee, National Natural Science Foundation, Doctoral Research Foundation of the Education Ministry of China, and Tsinghua University Press and Elsevier Inc. We also thank the postgraduates, undergraduates, technicians, and workers who worked with us and helped us with the experimental and theoretical research. In addition, I would like to give special thanks to my wife, retired professor Suying Qian, who not only patiently typed the entire manuscript, including many calculation tables and complicated equations, to form the original computer text, but also takes care thoughtfully of my life.

The experimental investigations, theoretical analyses, design, and calculation methods for concrete structures at elevated temperatures are still not completely satisfactory. Many problems need to be resolved with more extensive research. Because the authors' research results, understanding, and analysis abilities are limited, some errors may be found in this book. We are grateful to the specialists and readers for their comments and criticism.

Zhenhai Guo
Tsinghua University, Beijing

INTRODUCTION

0.1 THERMAL PROBLEMS IN STRUCTURAL ENGINEERING

Generally, a concrete structure works at room temperature within the construction period and during its long service life. The absolute value of its environmental temperature is low and does not fluctuate. A structure designed following the current codes[0-1] can satisfy the safety and service performance requirements. However, if the environmental temperature increases too much or the temperature difference varies periodically, the structure may fail as the service performance deteriorates or strength decreases. Sometimes a structure may suffer local damage or even collapse.

In structural engineering, thermal problems due to changes in temperature can be classified into three categories[0-2]:

1. The temperature changes periodically or occasionally beyond the normal value. For example, on a surface exposed to the sun in a high-rise or long-span building, the temperature increases when the sun shines and reduces when the sun sets, and the air around the building increases in the summer and decreases in the winter, which causes the interior of the structure to suffer periodic temperature differences. Because of the accumulation of hydration heat of cement in concrete during the hardening process, and the temperature variation caused by circumferential water, air, and sunshine, a nonuniform temperature field is formed in massive hydraulic structures (dams, etc.). Although the maximum temperature in the interior of these structures is not very high (generally less than 60 °C), the strain induced by the temperature change (±30 °C) is much larger than the value of the ultimate tensile strain of concrete.[0-3] This is sufficient to cause cracking of the concrete, increase deformation of the structure, induce redistribution of the internal forces, and influence the service performance of the building.
2. High temperature action is maintained for a long time within the working conditions of the building. For example, some structures in metallurgy and chemical industry workshops are subject to radiation of high temperatures throughout the year, and the temperature on the surface of the structure may reach 200 °C or even higher. When a chimney spurts smoke of high temperature, the temperature of the internal lining may reach 500–600 °C and the temperature on the external surface may reach 100–200 °C. In the reactor vessel and containment structures of a nuclear power plant, the temperature may reach 120 °C or even higher at local positions.
3. High temperature impact in a short time is caused by occasional accidents. For example, a fire in a building may last a few hours, and the maximum temperature of the fire may reach 1000 °C, even higher within only 1 h. If a chemical or nuclear explosion or an accident at a nuclear plant occurs, the temperature may reach several thousand degrees centigrade or even higher within a matter of seconds.

The structural temperature effects of the above three categories have different temperature ranges and variable rules, which cause considerable differences in the behavior of the material and structure and the level of structural damage. They can be dealt with using theoretical analyses, design methods, and structural construction, respectively. There are corresponding design codes or specifications[0-4,0-7] for practical use in many countries, but in China, there are design codes and research monographs[0-8,0-10] for the first two categories only. There is a design code[0-11] for fire prevention in a building, but it cannot deal with the analysis and design of the fire resistance of structures.

This book mainly deals with the third category of structural thermal problems. It introduces the experimental and theoretical research results on concrete and reinforcement materials and the concrete members and structures under high accidental temperatures (i.e., fire). The general regularity and mechanical mechanism of their behavior at elevated temperatures are also presented. Analysis methods and calculations are provided for the temperature fields, the resistant behavior of structural members, statically indeterminate structures at elevated temperatures, and damage evaluation after a fire. The related principles, analysis methods, and experimental data in the book can also be used as a reference for other categories of structural thermal problems.

0.2 HARMFULNESS AND RESOLUTION OF STRUCTURE AFTER FIRE

The discovery of fire accelerated the evolution of humankind, promoted civilization and social development, and led to technologic progress, economic development, and a prosperous modern society. However, loss of control of fire may result in catastrophe. In Chinese history, many cities were burnt down during wars, and cities built over several hundred years were ruined in one day. In England, the Great Fire in London (1667), caused by a fire in a bakery, brought disaster to one-third of the buildings in the city.

Different types of fire accidents cause enormous loss of human lives, natural resources, and social properties. Therefore, humankind has struggled with fire for a long time and accumulated many experiences and created effective ways to control it. In modern society, the techniques and equipment for fire prevention and extinguishment are constantly being updated and their efficiency and performance also improve constantly, as scientific techniques make progress. Nevertheless, serious fire accidents still occur for various natural, technical, and man-made reasons, and fires occur most frequently and cause the most damage to buildings in a populated city. For example, more than 10,000 building fires occur every year in China, causing the loss of more than 1000 lives and several billion Yuan in economic losses annually.

There are many causes of fire in buildings, e.g., lightning strikes, material self-combustion, dust explosion, loss of control of fire in residential and industrial settings, negligence in storage or use of fuel, mistakes in operating electrical equipment, failure of an aged insulating layer, a secondary accident after an earthquake or war, and even arson. Fire prevention should cover all aspects.

Fire is a combustion phenomenon caused after a combustible substance is inflamed and reacts intensely together with an oxidant, generally oxygen in the air. In the burning process, enormous heat is generated, the temperature of the surrounding air and various materials rises quickly, and some materials in the space may burn successively and a more serious fire may result. As the flames and smoke associated with high temperature evolve, the fire spreads to the adjacent spaces, even the whole building. When firefighters are successful, either all combustibles inside a building burn out, or oxygen is exhausted or isolated, with the effect that the fire declines gradually and is eventually extinguished. This describes one cycle of a fire accident but it is possible that burning and declining are repeated several times in one fire accident.

When a fire occurs in a building, the temperature increases, a nonuniform temperature field forms, and the structural material deteriorates in the interior of the structure. This causes damage and strength reduction at different levels in the structure. When the structure acts as the load-bearing and support system of the building, it should maintain sufficient strength for a certain time period during a fire, so that firefighters can fight the fire, rescue the injured and deceased victims safely, and save valuable property.

Therefore, it is considered that a structure fails in fire resistance, if one of three limit states[0-12,0-14] is reached:

1. The limit state of the load-bearing capacity. The load-bearing capacity of a structure is reduced at elevated temperatures, so that the service load can no longer be supported because of structural collapse, instability, or excessive deflection (e.g., 1/30th of the clear span).
2. The limit state of obstructing fire. The integrity of a structure is compromised by fire, wide cracks and holes are formed, and the spread of fire and smoke cannot be stopped.
3. The limit state of heat insulation. When the temperature on a surface unexposed to the fire of the structure increases excessively (e.g., 140 °C for an average value or 180 °C for the maximum value), it may cause a fire in the adjacent rooms and a fire spreads.

The time taken for a structural or architectural member to reach one of the three limits under fire following the standard time–temperature curve (Eqn. (5.1)) is called the endurance limit (in hours). According to the Code of Fire Prevention in Buildings,[0-11] a building can be classified into four grades depending on its importance, and the minimum endurance limit (0.5–4 h) is stipulated for different members.

Several types of materials are used in structural engineering. Timber structures are combustible, cannot prevent a fire, and can even enhance a fire after it has started. Although a steel structure is not combustible, the temperature of the steel members under fire rises quickly and causes loss of the load-bearing capacity or failure of local stability, even collapse of the whole structure, because heat conducts very quickly through steel and the structural members are composed of thin-wall shaped steel components and plates. However, the main part of reinforced concrete is concrete itself, which is a material of high heat inertia and the main structural members usually have thick sections. So, the temperature in the interior of the member elevates slowly during a fire and the temperature elevation of the reinforcement is delayed by the outer cover. Therefore, the loss of strength of the material is less significant, the load-bearing capacity of the member decreases slowly, and the fire-resistant behavior and the endurance limit of reinforced concrete structures are much better than for steel and timber structures.

If a fire continues for a long time, the damage and failure phenomena of different levels will appear successively in the concrete structure: cracking and loosening on the surface, damage to the sides and corners, explosive spalling of the cover, reinforcement exposure, member deflection, gradual separation of the surface layers from the main body, damage area penetrating into the interior of the member, and, finally, caving in, local holes, and ultimately collapse of the entire structure may result.

Many valuable lessons and experiences have been gained from previous fire accidents and effective methods to prevent and fight fire have been developed. However, preventing fire is not always possible, so one should also depend on effective methods to fight fires. After years of research, many effective measures have been created in both of these aspects:

1. Prevention of fire occurrence and spread. For example, maintaining sufficient distance between buildings, separating the longer and larger areas into several parts and building firewalls between them, selecting facilities and furniture made of incombustible materials, spraying or smearing fire-protective material on the surface of combustibles, installing hydrants and water systems, installing automatic alarms and sprinkler facilities, studying the regularity of combustion, and limiting the spread of fire.
2. Research and enhancement of the fire resistance of buildings and structural members. For example, establishing large testing furnaces for measuring the endurance limit of full-scale members, selecting reasonable materials and improving the detail in construction of the structure, setting up insulating material on the member surface, conducting

experimental and theoretical research systematically on the thermal behavior of the materials, investigating the behavior of the members and the structures at elevated temperatures and their analysis method, and developing practical methods to calculate the bearing capacity and endurance limit of the structure under fire.

In order to enhance and solve the fire resistance ability of the structure and its members, several development stages are conducted: during the initial stage, only the construction measures tested by experience are used, e.g., increasing the thickness of the concrete cover of the reinforcement and using heat-resisting concrete; at the next stage, large experimental installations are established for loading tests of full-scale members at elevated temperatures, and the endurance limit or bearing capacity of the structural member under fire is directly measured. A recent trend is to emphasize theoretical analysis based on the experimental investigation, which includes the development of thermal–mechanical constitutive models for the materials, determination of the time–temperature curve of fire, conducting nonlinear analysis of the transient temperature field, and analyzing the whole process of the structure and its members under fire. Because the behavior of concrete structures at elevated temperatures is quite complicated, the theoretical analysis is not yet satisfactory and more study and improvements are needed.

0.3 BEHAVIOR CHARACTERISTICS OF REINFORCED CONCRETE STRUCTURES AT ELEVATED TEMPERATURE

According to the existing results of experimental and theoretical research and the experience of engineering practice, the behavior of reinforced concrete structures at elevated temperatures (and fire) is considerably different from that at ambient temperature. The characteristics of reinforced concrete structures at elevated temperatures are as follows.

1. Temperature distributed nonuniformly in the interior

Since the thermal conductivity of concrete is low, the temperature on the surface of the structure rises very quickly during a fire, but the temperature in the interior increases slowly. So, a nonuniform temperature field is formed in the structure, especially a large temperature gradient in the outer layer. In addition, the temperature field varies continuously for the duration of the fire (see Part 2).

The main factors determining the temperature field of the structure are the temperature–time process, the shape and size of the members, and the thermal behavior of the concrete material. The internal forces, deformation, and small cracks in the structure have less influence on the temperature field. On the contrary, the temperature field of the structure influences considerably the internal forces, deformation, and its bearing capacity. Therefore, the analysis of the temperature field of a structure can be conducted independently and earlier than that of internal forces and deformation.

2. Serious deterioration of material behavior

The values of the strength and elastic modulus of concrete and reinforcement at elevated temperatures decrease considerably and the deformation of both materials increases correspondingly. In addition, the external damage of concrete, e.g., due to cracking, loosening, and spalling, appears successively and gradually becomes more severe as the temperature increases (see Part 1). This is the main cause of serious reduction in the bearing capacity and the endurance limit of the structure and its members at elevated temperatures.

3. Coupling effect of stress, strain, temperature, and time

When a structure at ambient temperatures is analyzed, it is necessary to study only the stress–strain relationship of the material. However, the value and the duration of high temperature strongly influence the strength and deformation of the material. Furthermore, different heating and loading histories cause various values of the strength and deformation of the material. A coupling effect is then composed of four factors: stress, strain, temperature, and time for the concrete. Therefore, in order to accurately analyze the behavior of the structure at elevated temperatures, it is necessary to develop a corresponding coupling thermal–mechanical constitutive relationship for concrete (see Part 3). This complicates the analysis of the structure and its members significantly.

4. Redistribution of the stress on the member section and the internal forces of the structure

The nonuniform temperature field of the member section inevitably results in unequal temperature strain and stress redistribution on the section. In a statically indeterminate structure, the temperature deformation of the material at high temperature is restrained by the adjacent material at a different temperature, and the joint and the support. So, the redistribution of internal forces (bending moment, shear force, axial force, and even torque) of the structure is serious. As the temperature changes with time, a continuous process of redistribution of internal forces is then set in motion. Finally, the failure mechanism and pattern of the structure is different from that at room temperature, which influences the ultimate bearing capacity of the structure at elevated temperatures (see Chapter 10).

5. Process and pattern of failure

Generally, a concrete structure under ambient temperatures fails slowly with apparent signs. The structure and its members at elevated temperatures fail suddenly because the deformation increases quickly, the failure duration is short, and fewer warning signs appear. The structural member after failure shows large residual deformation, which can be seen clearly by the naked eye (see Part 3).

REFERENCES

[0-1] National Standard of People's Republic of China, Code for Design of Concrete Structure GB 50010-2002, Construction Industry Press of China, Beijing (2002).

[0-2] Z. Guo, The Principle of Reinforced Concrete, Tsinghui University Press, Beijing (1999).

[0-3] Z. Guo, Strength and Deformation of Concrete (Experimental Basis and Constitutive Relationship), Tsinghua University Press, Beijing (1997).

[0-4] Federation International de la Précontrainte, The Design and Construction of Prestressed Concrete Reactor Vessels (March 1978), FIP/3/3.

[0-5] ASME Boiler and Pressure Vessels Code, An American National Standard (ACI Standard 359–374). Section III, Division 2 (January 1975).

[0-6] Federation International de la Précontrainte, FIP/CEB Recommendations for the Design of Reinforced and Prestressed Concrete Structural Members for Fire Resistance, FIP/1/1 First ed. (June 1975).

[0-7] Federation International de la Précontrainte, FIP/CEB Report on Methods of Assessment of the Fire Resistance of Concrete Structural Members, FIP, (1978).

[0-8] Professional Standard of Electric Industry of People's Republic of China, Design Code for Hydraulic Concrete Structures DL/T 5057–1996, Electric Power Press of China, Beijing (1997).

[0-9] B. Zhu, T. Wang, B. Ding, Z. Guo, Thermal Stress and Temperature Control of Hydraulic Concrete Structure, Hydraulic and Electric Power Press, Beijing (1976).

[0-10] Professional Standard of Metallurgical Industry of People's Republic of China, Code for Heat-Resistance Design of Reinforced Concrete Structure of Metallurgical Workshop YS12-79 (Tentative), Metallurgical Industry Press, Beijing (1979).

[0-11] National Standard of People's Republic of China, Code for Architectural Design of Fire Prevention GBJ 16-87, Construction Industry Press of China, Beijing (1988).

[0-12] S. Wang (Ed.), Fire Prevention of Building, Construction Industry Press of China, Beijing (2000).

[0-13] B.K. Bardhan-Roy, Fire resistance—design and detailing, in: F.K. Kong (Ed.), Handbook of Structural Concrete, Pitman, London (1983) 14-1–14-46.

[0-14] Y. Li, D. Ma, J. Xu, Calculation and Construction for Fire Prevention Design of Building Structure, Construction Industry Press of China, Beijing (1991).

Experiment and Calculation of Reinforced Concrete at Elevated Temperatures

CONTENTS

PART II Temperature Field on a Cross Section of a Structural Member