STEEL CORROSION-INDUCED CONCRETE CRACKING

钢筋锈蚀引起的混凝土开裂

Yuxi Zhao
Weiliang Jin

科学出版社

Steel Corrosion-Induced Concrete Cracking

钢筋锈蚀引起的混凝土开裂

Yuxi Zhao
Zhejiang University, Hangzhou, China

Weiliang Jin
Zhejiang University, Hangzhou, China

ELSEVIER

Butterworth-Heinemann
An imprint of Elsevier
elsevier.com

Science Press
Beijing

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

ISBN: 978-7-03-047437-7
Science Press, Beijing

ISBN: 978-0-12-809197-5
Butterworth-Heinemann, an imprint of Elsevier

Published by Science Press
16 Donghuangchenggen North Street
Beijing 100717, P.R.China
Printed in Beijing

Foreword

Service life of unreinforced concrete structures can be extremely long. Many historical structures from the Roman period demonstrate this fact convincingly, such as the Pantheon in Rome, which is built of high-strength concrete, normal concrete, and a cupola of extremely lightweight concrete, or Roman bridges all over Europe. They have survived thousands of years under the effects of natural exposure, wars, and earthquakes without protection or maintenance.

If steel reinforcement is embedded in concrete, then the steel is protected initially by a surface passivation layer in the aqueous pore solution because of its high pH value. This passivation layer, however, is not stable in aging concrete. Concrete is a porous material. At first, the pore space is partially filled with water and is in equilibrium with high relative humidity. However, the surface of reinforced concrete structures is often exposed to an atmosphere with much lower humidity. As a consequence, a long-lasting drying process begins as soon as the formwork is removed. As the pore space is partially emptied, gases diluted in the surrounding air such as CO_2 will slowly migrate into the pore space and react with the young cement-based matrix. First, a thin layer of carbonated hydration products is formed near the surface. When the growing thickness of this carbonated layer reaches the cover thickness, the pH value of the pore liquid in contact with the steel reinforcement is lowered and the protective passivation layer is eventually destroyed. Hence, corrosion is initiated.

If the surface of concrete is temporarily in contact with an aqueous chloride solution such as sea water or water containing dissolved deicing salt, then chloride ions can penetrate into the pore space of the concrete. Fortunately, the chloride ions are filtered out of the salt solution and they are enriched close to the surface; however, the clean water may penetrate deep into the pore space by capillary action. Later, dissolved chloride ions migrate deeper into the nanoporous material by slow diffusion. Whenever the chloride concentration near the steel reinforcement reaches a critical value, the protective passivation layer may be locally destroyed and corrosion of steel begins.

Until now, durability design had not reached the sophisticated level of structural design. Usually one considers different stages, for instance, corrosion initiation, crack formation, and spalling. After initiation, the rate of

corrosion may be rather low. But after the first cracks are generated, corrosion will be significantly accelerated. The authors of this book primarily describe the formation of corrosion products and the time-dependent pressure built up by the voluminous corrosion products. These are essential processes that may serve as indications of the end of service life of reinforced concrete structures.

The mechanisms of steel corrosion in concrete are briefly described. The following chapters describe in great detail the formation of corrosion products at the interface between steel and concrete. In particular, the gradual filling of the pores of hardened cement paste and the gradual filling of cracks with corrosion products are considered. Finally, a model describing concrete cracking due to the formation of corrosion products is presented. This approach and the results obtained by the two authors of this book will be very helpful for more realistic prediction of the service life of reinforced concrete structures.

In this book, the complex processes that can be observed during the critical period of aging concrete between corrosion initiation and crack formation in the concrete cover and then, finally, spalling of the layer near the surface are described in great detail for the first time. A better understanding of these complex processes will contribute to the development of more reliable prediction of service life and of more efficient methods for protective interventions. Therefore, the service life of reinforced concrete structures can be extended systematically and the cost of repair measures can be substantially reduced. This is of particular importance for countries like China, in which a nationwide infrastructure is rapidly being built. In no other country is more concrete being produced at this moment.

If modern construction does not become more sustainable, and if the service life of reinforced concrete structures is not significantly extended, then further development will be slowed because of the enormous costs for repair and maintenance of the existing infrastructure. This book may contribute a great deal to finding realistic and sustainable solutions to this worldwide problem.

This volume deserves wide distribution and will hopefully be studied in great detail by scientists and practitioners. With this book, the actual situation concerning durability and service life in construction can be improved substantially worldwide.

Folker H. Wittmann

Preface

Since the mid 1970s, a number of durability-related problems have emerged and stimulated research of the key factors that relate to the durability problems of concrete structures. Reinforcing steel corrosion is one of the major reasons for deterioration of reinforced concrete structures. Steel corrosion in concrete will induce sectional loss of steel bar, degradation of bond stress between steel and concrete, and cracks parallel to longitudinal bars. Field studies have suggested that cracking and spalling are most concerning to asset owners. Structural collapse of reinforced concrete structures due to steel corrosion is rare; cracking, rust staining, and spalling of the concrete cover usually appear well before a reinforced concrete structure is at risk. Therefore, the cracking of the concrete cover induced by steel corrosion is important and is usually defined as the serviceability limit state.

The authors have focused on this research field since 1998, and have carefully investigated the origin, mechanism, and development of corrosion-induced cracking in concrete. Considering the importance of this topic, the authors summarize the related research achievements obtained and share with other researchers and engineers who are interested in this field. This book concentrates on the concrete cracking process induced by steel corrosion. After the background introduction and literature review in chapter "Introduction," the mechanisms of steel corrosion in concrete are introduced in chapter "Steel Corrosion in Concrete." The composition, expansion coefficient, and elastic modulus of steel corrosion are carefully investigated in chapter "The Expansion Coefficients and Modulus of Steel Corrosion Products," considering the importance of the properties of steel corrosion in concrete cracking models. With these parameters of steel corrosion, the damage analysis is applied to analyze the corrosion-induced concrete cracking process in chapter "Damage Analysis and Cracking Model of Reinforced Concrete Structures With Rebar Corrosion," and the critical thickness of the rust layer at the moment of surface cracking of concrete cover is studied in chapter "Mill Scale and Corrosion Layer at Concrete Surface Cracking." In chapter "Rust Distribution in Corrosion-Induced Cracking Concrete," the authors investigate the rust distribution in the corrosion-induced cracks and find that the rust did not fill the corrosion-induced cracks in the concrete cover before concrete surface cracking. A Gaussian function is proposed to describe the nonuniform spatial distribution of corrosion products in chapter

"Nonuniform Distribution of Rust Layer Around Steel Bar in Concrete." The shape of the corrosion-induced cracks in the concrete cover is observed in chapter "Crack Shape of Corrosion-Induced Cracking in the Concrete Cover," and a linear model was proposed to describe the variation in the total circumferential crack width along the radial direction in the concrete cover. Rust distribution at the steel–concrete interface is presented in chapter "Development of Corrosion Products-Filled Paste at the Steel–Concrete Interface"; and the penetration of corrosion products into the porous zone of concrete and formation of a corrosion layer at the steel–concrete interface process simultaneously. Finally, in chapter "Steel Corrosion-Induced Concrete Cracking Model," an improved corrosion-induced cracking model is proposed, which considers the corrosion layer accumulation and corrosion products filling occurring simultaneously in concrete. The time from corrosion initiation to concrete surface cracking is discussed. The need for more research regarding the corrosion-induced cracking model is also discussed in this book.

The authors hope this book is useful for researchers interested in the durability of concrete and concrete structure fields, for industry engineers who pay attention to the deterioration mechanisms and the life cycle of reinforced concrete structures, and for graduate students whose research topics include corrosion-induced deterioration of reinforced concrete structures.

Acknowledgments

Continuous financial support from the National Science Foundation of China (NSFC) through grants 50538070, 50920105806, 50808157, and 51278460 is gratefully acknowledged. Without this financial support, it would be not possible to perform all the experimental work, develop the analytical models, and further the research in this area.

The authors also express sincere gratitude to the graduate students who contributed their talent, intelligence, effort, and hard work to this research. They are Haiyang Ren, Jiang Yu, Bingyan Hu, Hong Dai, Yingyao Wu, Hangjie Ding, Jianfeng Dong, and Xiaowen Zhang. Particular thanks are expressed to Hangjie Ding, Jianfeng Dong, and Xiaowen Zhang, who also helped to edit the contents, improve the format, and modify some figures in this book.

We appreciate the comments and encouragement from Professor Folker H. Wittmann, his comments improve the quality of the book, he also kindly wrote the *Foreword*. Many thanks to the reviewers of this book for their time. Their helpful suggestions have strengthened the book considerably. Our thanks also go to the publisher and the editor Fanjie Wu, who patiently replied to all our questions and helped us as much as possible.

We apologize for naming such a small number of the many people who helped us and with whom we had the pleasure of working. Sincere thanks to all of them for their willingness to share their knowledge with us and for encouraging us to go further and further in this area.

List of Figures

List of Tables

Contents