Yu-Qiu Long
Song Cen
Zhi-Fei Long

Advanced Finite Element Method in Structural Engineering

Yu-Qiu Long
Song Cen
Zhi-Fei Long

Advanced Finite Element Method in Structural Engineering

With 219 figures

TSINGHUA UNIVERSITY PRESS

Springer

AUTHORS:

Yu-Qiu Long
Department of Civil Engineering of
Tsinghua University
100084 Beijing China

Song Cen
School of Aerospace of
Tsinghua University
100084 Beijing China

Zhi-Fei Long
School of Mechanics & Civil Engineering of
China University of Mining & Technology
100083 Beijing China

ISBN 978-7-302-18889-6 **Tsinghua University Press, Beijing**
ISBN 978-3-642-00315-8 **Springer Berlin Heidelberg New York**
e ISBN 978-3-642-00316-5 **Springer Berlin Heidelberg New York**

Library of Congress Control Number: 2009921171

Co-published by Tsinghua University Press, Beijing and Springer-Verlag GmbH Berlin Heidelberg

Springer is a part of Springer Science+Business Media
springer.com

Cover design: Frido Steinen-Broo, EStudio Calamar, Spain
Printed on acid-free paper

Yu-Qiu Long
Song Cen
Zhi-Fei Long

新型有限元论

——结构工程中的高等有限元方法

Advanced Finite Element Method in Structural Engineering

TSINGHUA UNIVERSITY PRESS
Springer

内 容 简 介

本书是在中文专著《新型有限元论》（2004 年版）的基础上补充了 2004 年至 2008 年期间的新成果所撰写的英文专著，是龙驭球院士、岑松博士和龙志飞教授及其研究组多年来在新型有限元方面研究成果的系统论述。全书分为 20 章。除首尾两章外，其余 18 章分为 3 篇：第 1 篇是变分原理进展，介绍分区和含参变分原理 2 项成果；它们为构造新型有限元起到理论指导作用。第 2 篇是有限元法进展初论，重点介绍广义协调元；这是在协调元与非协调元之间另辟的新路，使协调问题和收敛问题得到合理解决，单元构造方案可以灵活优选，学科内容得到充实更新；广义协调元是新型有限元方面的主要成果，在本书中起核心作用。第 3 篇是有限元法进展续论，补充介绍 4 项成果，包括分区混合元法、解析试函数法、第一和第二类四边形面积坐标法和样条函数有限元法，在本书中起锦上添花作用。本书还结合 7 项成果的论述，介绍了总共 108 个相关的新单元。

本书可作为高等学校力学、土木、机械等专业研究生和高年级本科生的教材和参考书，也可供相关领域教师和科技人员参考。

图书在版编目(CIP)数据

新型有限元论——结构工程中的高等有限元方法= Advanced Finite Element Method in Structural Engineering: 英文/龙驭球，岑松，龙志飞著. —北京：清华大学出版社，2008.12
ISBN 978-7-302-18889-6

Ⅰ.新… Ⅱ.①龙… ②岑… ③龙… Ⅲ.有限元分析–英文 Ⅳ.O241.82

中国版本图书馆 CIP 数据核字(2008)第 175870 号

责任编辑：徐晓飞　王海燕
责任校对：王淑云
责任印制：孟凡玉

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：153×235　**印张**：45　**字数**：1042 千字
版　　次：2008 年 12 月第 1 版　**印次**：2008 年 12 月第 1 次印刷
印　　数：1～800
定　　价：128.00 元

本书如存在文字不清、漏印、缺页、倒页、脱页等印装质量问题，请与清华大学出版社出版部联系调换。联系电话：010-62770177 转 3103　产品编号：031557-02

Professor Yu-Qiu Long (1926—) is a Full Professor in the Department of Civil Engineering, Tsinghua University, and also a Member of the Chinese Academy of Engineering since 1995. During the past 60 years, he has been recognized as an expert in the areas of structural mechanics, shell structures, finite element method and variational principle. He was the first President of the Chinese Association of Structural Engineering between 1998 and 2003; Council Member of the Chinese Association of Computational Mechanics from 1957 to 1990; and Editor-in-Chief of a Chinese journal, *Engineering Mechanics*, between 1991 and 1999. He is currently a member of Editorial Boards of many international and Chinese journals, such as *Advances in Structural Engineering* (since 1997), *International Journal of Structural Stability and Dynamics* (since 2001), *Applied Mathematics and Mechanics* (since 1979), and so on. He published his first book on the finite element method in 1978, which is one of the earliest books on this subject in China and has a broad influence on Chinese readers.

Dr. Song Cen (1972—) is serving as an Associate Professor in the Department of Engineering Mechanics, School of Aerospace, Tsinghua University. He is also the deputy secretary-general of Beijing Society of Mechanics; Executive Council Member of the International Chinese Association for Computational Mechanics; Invited Council Member of the Chinese Association of Computational Mechanics. His research interests mainly cover finite element method and computational solid mechanics. Dr. Cen is a recipient of some prestigious Prizes for distinguished young Chinese researchers, including *Xu Zhi-Lun Prize in Mechanics* (2007), *New Academic Prize of Tsinghua University* (2007), *Fok Ying Tung Prize for Young Researchers in Universities* (2006), *the Nationwide* (China) *Excellent Doctoral Dissertation Award of Year 2002* (supervised by Professor Yu-Qiu Long), and so on.

Professor Zhi-Fei Long (1957—) is a professor in the School of Mechanics & Civil Engineering, China University of Mining & Technology (Beijing). He is an expert in finite element method and structural mechanics, and has published 4 books and more than 90 papers in related fields. He won the Science Award of China Ministry of Education (First Class, 1993), for the studies on the generalized energy principles and new finite element models. The textbook titled by New Monograph of Finite Element Method (written by Zhi-Fei Long and Song Cen, published by China Hydraulic and Water-power Press in 2001) has produced a broad influence in Chinese universities.

Preface

The main purpose of this book is to describe some developments in finite element method and related variational principles. Since this book only deals with the areas the authors are familiar with, it is impossible to cover every aspect of these subjects. This book is composed of 20 chapters. Except for *Introduction* (Chap. 1) and *Concluding Remarks* (Chap. 20), in the other 18 chapters, seven theoretical achievements (two achievements in variational principles and five achievements in finite element methods are introduced, which are subdivided into three Parts.

Part Ⅰ focuses on advances in the variational principles. Two innovations in this subject are discussed here.

(1) *Sub-region variational principles* (Chap. 2). The concept of *sub-region* is introduced for establishing new variational principles suitable for the developments of the finite element method.

(2) *Variational principles with several adjustable parameters* (Chap. 3). Several adjustable parameters are included in the variational principles so that a broader optimization space is available.

Part Ⅱ focuses on the main advances in the finite element method—generalized conforming elements (the third innovation). Eight chapters are employed to illustrate this innovation.

(3) *Generalized conforming elements* (Chaps. 4－11). Firstly, from the viewpoint of theory, the generalized conforming element opens a new way between conforming and non-conforming elements, so that the puzzle of the convergence problem for non-conforming elements can be rationally solved. Meanwhile, various new conforming schemes, including point conforming, line conforming, perimeter conforming, SemiLoof conforming, least square conforming and their combination forms, have been successfully proposed. Secondly, from the viewpoint of applications, the successful application of the generalized conforming element method was first realized for thin plate bending problem, in which a series of high performance thin plate element models were presented. Subsequently, the novel technique was successfully generalized to other fields, and a large number of new models, including membrane elements, membrane elements with drilling DOFs, thin-thick plate elements, laminated composite plate elements, flat-shell

elements, curved shell elements, etc., were also successfully constructed.

Part Ⅲ focuses on the other advances in the finite element method. Eight chapters are employed to discuss four additional subject innovations.

(4) *Sub-region mixed element method* (Chaps. 12 – 13). It provides a novel solution strategy for fracture problem by complementarity and coupling of displacement-based element and stress-based element.

(5) *Analytical trial function method* (Chaps. 14 – 15). This method exhibits rewarding cooperation between analytical and discrete methods, and provides effective solution strategy for shear locking, trapezoidal locking, and singular stress problems.

(6) *Quadrilateral area coordinate method* (Chaps. 16 – 17). This method indicates that the area coordinate method is generalized from the traditional triangular element field to new fields.

(7) *Spline element method* (Chaps. 18 – 19). This method indicates that the advantages of the spline functions have been adopted by the finite element method.

While introducing above seven theoretical innovations, five new element series with 108 new element models, which were directly derived from the five achievements in FEM, are also discussed in detail or briefly (see Table 20.2). Furthermore, based on these developments, effective solution strategies for five challenging problems (shear-locking problem in thick plate elements, sensitivity problem to mesh distortion, non-convergence problem of non-conforming elements, accuracy loss problem of stress solutions by displacement-based elements, and singular stress problem) have also been found.

To sum up, in the contents of this book, three aspects should be emphasized:

(1) Seven new achievements in the field of variational principle and FEM;

(2) five new element series with 108 new element models;

(3) five sets of novel solution strategies for five challenging problems.

The authors are very grateful to all the colleagues and students who made significant contributions to the contents included in this book. We also thank China Academy of Building Research for compiling our algorithms and finite element models into their FEM software product, SATWE, for designs of high-rise building structures.

Our research activities were financially supported by many foundations and sponsors. We list them below and express our deep gratitude.

- The National Natural Science Foundation of China (Math85287; 58978341; 59578031; 59878022; 10272063; 10502028; 10872108)
- The Special Foundation for the Authors of the Nationwide (China) Excellent Doctoral Dissertation (200242)
- The Program for New Century Excellent Talents in Universities of China (NCET-07-0477)
- Basic Science Research Foundation of Tsinghua University (JC1999002; JC2002003)
- China Postdoctoral Science Foundation (12836).
- The Special Scientific Foundation for Chinese Doctoral Education (97000315; 20020003044)

Contents