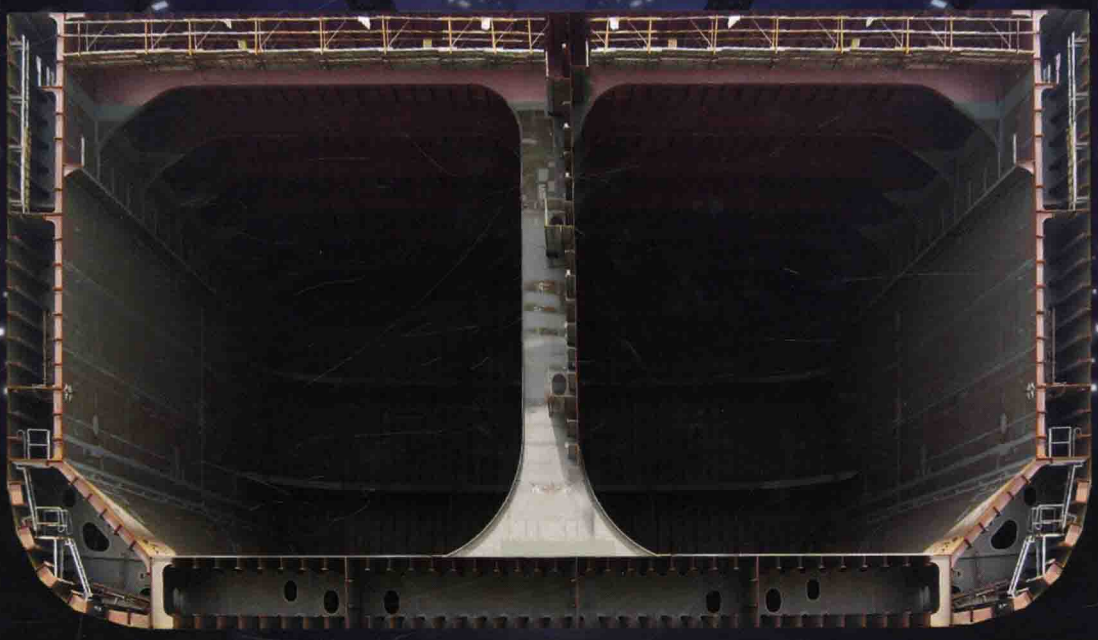
# ULTIMATE LIMIT STATE ANALYSIS AND DESIGN OF PLATED STRUCTURES

SECOND EDITION



JEOM KEE PAIK

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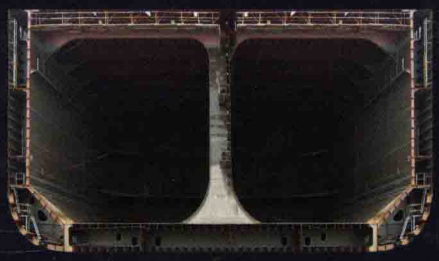

SECOND EDITION

**JEOM KEE PAIK**
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Plated structures are important in a variety of marine, land-based and aerospace applications, including ships, offshore platforms, box girder bridges, power/chemical plants, box girder cranes, and aircrafts. The basic strength members in plated structures include support members (such as stiffeners, girders and frames), plates, stiffened panels, grillages, box columns, and box girders. During their lifetime, the structures constructed with these members are subjected to various types of action and action effects that are usually normal but sometimes extreme or even accidental.

It is now well recognized that the limit state approach is a much better basis for structural design than allowable working stresses and simplified buckling checks for structural components. This book reviews and describes both the fundamentals and practical procedures for the ultimate limit state analysis and design of steel- and aluminum-plated structures. Structural fracture mechanics and structural impact mechanics are also described. This book is an extensive update of the first edition *Ultimate Limit State Design of Steel-Plated Structures,* published in 2003.

Particularly valuable coverage in this book includes:

- Nonlinear structural mechanics, and limit state analysis and design of steel- and aluminum-plated structural systems and their components
- Progressive collapse analysis and design of damage tolerant structures against extreme and accidental conditions
- Fabrication related initial imperfections such as initial distortions, residual stresses and softening
- Age related degradation such as corrosion wastage and fatigue cracking
- Accident induced damages such as local denting, collision damage and grounding damage
- Low temperatures, cryogenic conditions and elevated temperatures
- Structural fracture mechanics
- Structural impact mechanics
- Incremental Galerkin method
- Nonlinear finite element method and intelligent supersize finite element method

Designed as both a textbook and a handy reference, this book is well suited for university students approaching the related technologies. In terms of the more advanced and sophisticated design methodologies presented, this book should also meet the needs of structural analysts, structural designers, researchers, and practicing engineers involved in the field of naval architecture and offshore, civil, architectural, mechanical, and aerospace engineering.

**DR. JEOM KEE PAIK** is Professor of Marine Technology in the Department of Mechanical Engineering at University College London in the UK and Professor of Safety Design and Engineering in the Department of Naval Architecture and Ocean Engineering at Pusan National University in Korea. He is an honorary professor at University of Strathclyde, Glasgow, UK, and at Southern University of Science and Technology, Shenzhen, China.

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PAIK

# ULTIMATE LIMIT STATE ANALYSIS AND DESIGN OF PLATED STRUCTURES

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# Ultimate Limit State Analysis and Design of Plated Structures

Second Edition

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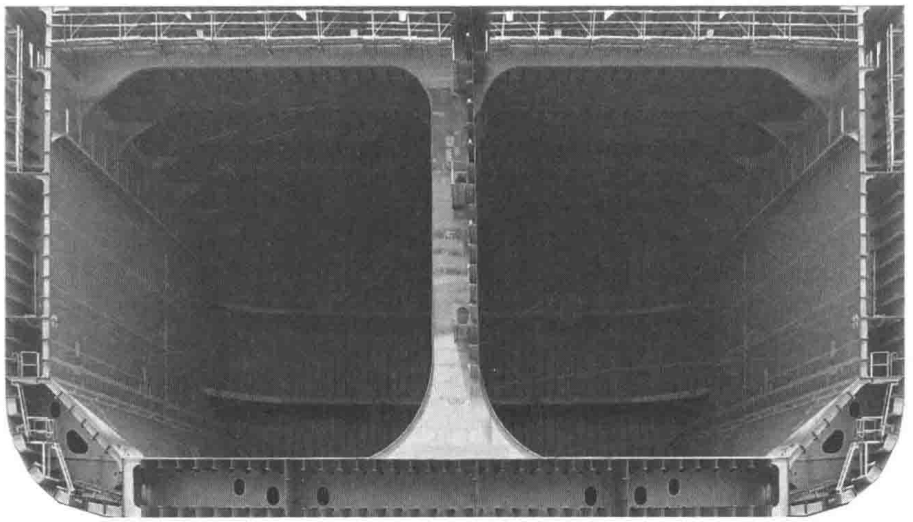

# Preface

Plated structures are important in a variety of marine- and land-based applications, including ships, offshore platforms, box girder bridges, power/chemical plants, and box girder cranes. The basic strength members in plated structures include support members (such as stiffeners and plate girders), plates, stiffened panels, grillages, box columns, and box girders. During their lifetimes, the structures constructed with these members are subjected to various types of actions and action effects that are usually normal but sometimes extreme or even accidental.

In the past, criteria and procedures for designing plated structures were primarily based on allowable working stresses and simplified buckling checks for structural components. However, it is now well recognized that the limit state approach is a better basis for design because it is difficult to determine the real safety margin of any structure using linear elastic methods alone. It also readily follows that it is of crucial importance to determine the true limit state if one is to obtain consistent measures of safety that can then form a fairer basis for comparison of structures of different sizes, types, and characteristics. An ability to better assess the true margin of safety would also inevitably lead to improvements in related regulations and design requirements.

Today, the preliminary design of ships including naval and merchant vessels, offshore structures such as ship-shaped offshore installations, mobile offshore drilling units, fixed-type offshore platforms and tension leg platforms, and land-based structures such as bridges and box girder cranes tends to be based on limit state considerations, including the ultimate limit state.

To obtain a safe and economic structure, the limit state-based capacity and structural behavior under known loads must be assessed accurately. The structural designer can perform such a relatively refined structural safety assessment even at the preliminary design stage if simple expressions are available for accurate prediction of the limit state behavior. A designer may even desire to do this for not only the intact structure but also structures with premised damage to assess their damage tolerance and survivability.

Although most structural engineers in the industry are very skilled and well experienced in the practical structural design aspects based on the traditional criteria, they may need a better background in the concept of limit state design and related engineering tools and data. Hence, there is a need for a relevant engineering book on the subject that provides an exposition of basic knowledge and concepts. Many structural specialists in research institutes continue to develop more advanced methods for the limit state design of plated structures, but they sometimes lack the useful engineering data to validate them. Students in universities want to learn more about the fundamentals and

practical procedures regarding the limit state analysis and design and thus need a book that provides useful insights into the related disciplines.

This book reviews and describes both the fundamentals and practical procedures for the ultimate limit state analysis and design of ductile steel-plated and aluminum-plated structures. Structural fracture mechanics and structural impact mechanics are also described. This book is an extensive update of my previous book *Ultimate Limit State Design of Steel-Plated Structures* (with Dr. A.K. Thayamballi), published in 2003. In contrast to the previous book, this update covers both steel- and aluminum-plated structures together with the latest advances and many newly added materials not included in the 2003 version. The book is basically designed as a textbook. The derivation of the basic mathematical expressions is presented together with a thorough discussion of the assumptions and the validity of the underlying expressions and solution methods.

I believe that the reader should be able to obtain insight into a wider spectrum of ultimate limit state analysis and design considerations in both an academic and a practical sense. In part, this book is an easily accessible analysis and design toolbox that facilitates learning by applying the concepts of the ultimate limit state for practice.

This book is primarily based on my own insights and developments obtained from more than 35 years of professional experience, as well as information and findings provided by numerous other researchers and limit state design practitioners. Wherever possible, I have tried my best to acknowledge the invaluable efforts of other investigators and practitioners, and, if I have failed anywhere in this regard, I did so inadvertently.

I gratefully acknowledge all those individuals who helped make this book possible. Most of all, Dr. A.K. Thayamballi, who was the coauthor of the previous book, provided valuable and comprehensive comments to improve this book. Finally, I take this opportunity to thank my wife Yun Hee Kim, my son Myung Hook Paik and my daughter Yun Jung Paik for their unfailing patience and support while this book was being written.

October 2017

*Prof. Jeom Kee Paik, Dr. Eng., CEng, DHC (ULieg), FRINA, LFSNAME*
*Pusan National University*
*and University College London*

## About the Author

Dr. Jeom Kee Paik is a professor and faculty member of both the Department of Naval Architecture and Ocean Engineering of Pusan National University (PNU) in Korea and the Department of Mechanical Engineering of University College London in the United Kingdom. He is an honorary professor both at University of Strathclyde in the United Kingdom and at Southern University of Science and Technology in China. He was a visiting professor at Technical University of Denmark, Virginia Polytechnic Institute and State University, USA, and University of Newcastle, Australia.

Prof. Paik founded two key institutions: the Korea Ship and Offshore Research Institute (KOSORI) (http://www.kosori.org) at PNU, which has been a Lloyd's Register Foundation Research Centre of Excellence (ICASS, International Centre for Advanced Safety Studies, http://www.icass.kr) since 2008, and the Forum for Safety of Fire and Explosion (http://www.safeforum.co.kr) under the Ministry of Interior and Safety of Korea. He also serves as president and chairman, respectively. He is founder and editor-in-chief of *Ships and Offshore Structures* (http://saos.edmgr.com), which is a peer-reviewed international journal published by Taylor & Francis, UK. He is cofounder and cochairman of the International Conference on Ships and Offshore Structures (http://www.iscos.info), which is an annual event associated with the *Ships and Offshore Structures* journal.

Prof. Paik received Bachelor of Engineering degree from Pusan National University, Korea and Master of Engineering and Doctor of Engineering degrees from Osaka University, Japan. Prof. Paik is a life fellow, fellows committee member, Marine Technology board member, and vice president of the US Society of Naval Architects and Marine Engineers (SNAME), and a fellow, council member, publications committee member, and Korean branch chairman of the UK Royal Institution of Naval Architects (RINA).

Prof. Paik's research interests include nonlinear structural mechanics, analysis, and design; advanced safety studies; limit state-based design; structural reliability; risk assessment and management; health condition assessment and management; fires, explosions, collisions, grounding, dropped objects, and impact engineering; corrosion assessment and management; structural longevity; inspection and maintenance; and decommissioning.

Prof. Paik has authored or coauthored more than 500 technical papers including over 270 peer-reviewed journal articles. He is the coauthor or coeditor of four books: *Ultimate Limit State Design of Steel-Plated Structures* (with A.K. Thayamballi), John Wiley & Sons, 2003; *Ship-Shaped Offshore Installations: Design, Building, and Operation* (with A.K. Thayamballi), Cambridge University Press, 2007; *Condition Assessment of Aged Structures* (with R.E. Melchers), CRC Press, 2009; and *Ship Structural Analysis and Design* (with O.F. Hughes), SNAME, 2013. He also obtained numerous patents based on his research studies over a wide range of topics in naval architecture and ocean engineering.

Among other recognitions, Prof. Paik received both the William Froude Medal of the RINA (2015) and the David W. Taylor Medal of the SNAME (2013), the two most prestigious medals in the global maritime community in recognition for his contributions to naval architecture and ocean engineering. He was conferred the Doctor Honoris Causa (Honorary Doctorate) by the University of Liege in Belgium (2012) in recognition for his contributions to international science, engineering, and technology. Prof. Paik was awarded the Republic of Korea Order of Science and Technology Merit (2014). He has received numerous (13) best paper awards and engineering prizes from the SNAME, the RINA, the UK Institution of Mechanical Engineers, the American Society of Mechanical Engineers, and the Society of Naval Architects of Korea. He was also awarded the Kyung-Ahm Prize (2013) from the Kyung-Ahm Education and Culture Foundation. As a very special honor for a living figure, the RINA created a prize named in honor of Prof. Paik, the *Jeom Kee Paik Prize*, which has been awarded each year since 2015 for the best paper on structures published by a researcher under 30 years of age; the prize is the first of its kind named for a non-Briton in the RINA's 156-year history.

Prof. Paik has served in numerous international engineering societies in various capacities. He served as editor-in-chief of UNESCO's Encyclopedia of Life Support System with EOLSS 6.177 Ships and Offshore Structures in 2006–2011. He served as chairman of the Korean Shipbuilding Advisory Committee of Registro Italiano Navale (Italian Classification Society) in 2013–2014 and the numerous technical committees of the International Ship and Offshore Structures Congress (ISSC) associated with Ship Collisions and Grounding (2000–2003), Condition Assessment of Aged Ships (2003–2006), and Ultimate Strength (2006–2012). He has presided numerous international conferences, including the International Conference on Thin-Walled Structures (ICTWS 2014, Busan, Korea) and the International Conference on Ocean, Offshore, and Arctic Engineering (OMAE 2016, Busan, Korea), and has cochaired the International Conferences on Ships and Offshore Structures. He will chair the upcoming International Symposium on Plasticity and Impact Mechanics (IMPLAST 2019, Busan, Korea). Currently, Prof. Paik heads the Korean Technical Committee of ClassNK (Japanese Classification Society), is a member of the Academic Advisory Council of Universiti Teknologi PETRONAS in Malaysia and of the ISSC Standing Committee, and is an editorial board member for more than 20 international journals.

## How to Use This Book

Written to develop a textbook and handy source for the principles behind the ultimate limit state analysis and design of steel- and aluminum-plated structures, this book is designed to be well suited for university students approaching the related technologies. In terms of the more advanced and sophisticated analysis and design methodologies presented, this book should also meet the needs of structural analysts, designers, or researchers involved in the field of naval architecture and offshore, civil, architectural, aerospace, and mechanical engineering.

Hence, apart from its value as a ready reference and an aid to continuing education for established practitioners, this book can be used as a textbook for teaching courses on ultimate limit state analysis and design of plated structures at the university level, as it covers a wide enough range of topics that may be considered for more than one semester course.

A teaching course of 45 h for undergraduate students in structural mechanics or thin-walled structures may cover Chapter 1, "Principles of Limit State Design"; Chapter 2, "Buckling and Ultimate Strength of Plate–Stiffener Combinations: Beams, Columns, and Beam–Columns"; Chapter 3, "Elastic and Inelastic Buckling Strength of Plates Under Complex Circumstances"; Chapter 5, "Elastic and Inelastic Buckling Strength of Stiffened Panels and Grillages"; Chapter 7, "Buckling and Ultimate Strength of Plate Assemblies: Corrugated Panels, Plate Girders, Box Columns, and Box Girders"; and Chapter 8, "Ultimate Strength of Ship Hull Structures."

For postgraduate students who pass the teaching course for the undergraduate students noted previously, a more advanced course of 45 h may cover Chapter 1, "Principles of Limit State Design" (repeated); Chapter 2, "Buckling and Ultimate Strength of Plate–Stiffener Combinations: Beams, Columns, and Beam–Columns" (repeated); Chapter 4, "Large Deflection and Ultimate Strength Behavior of Plates"; and Chapter 6, "Large Deflection and Ultimate Strength Behavior of Stiffened Panels and Grillages."

In teaching courses, lecturers are advised to guide students to practice the derivations of important formulations described in each chapter together with practical problems for analysis and design of steel- and aluminum-plated structures. Students may submit homework reports to the lecturers, an exercise that would be helpful for students to better understand the fundamentals and practical applications.

Chapter 9, "Structural Fracture Mechanics," and Chapter 10, "Structural Impact Mechanics," should also be useful in association with fatigue limit state design and accidental limit state design, respectively. These two chapters are supplementary for

the ultimate limit state analysis and design, as they describe the fundamentals and practices of fatigue and accidental limit states. Chapter 11, "The Incremental Galerkin Method"; Chapter 12, "The Nonlinear Finite Element Method"; and Chapter 13, "The Intelligent Supersize Finite Element Method," should be useful for postgraduate students, researchers, and practicing engineers given their more refined and sophisticated analyses of the ultimate strength behavior of plated structures.

The author has attempted to fulfill these many lofty aims in developing this book. He sincerely hopes his efforts prove successful, however modestly.

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