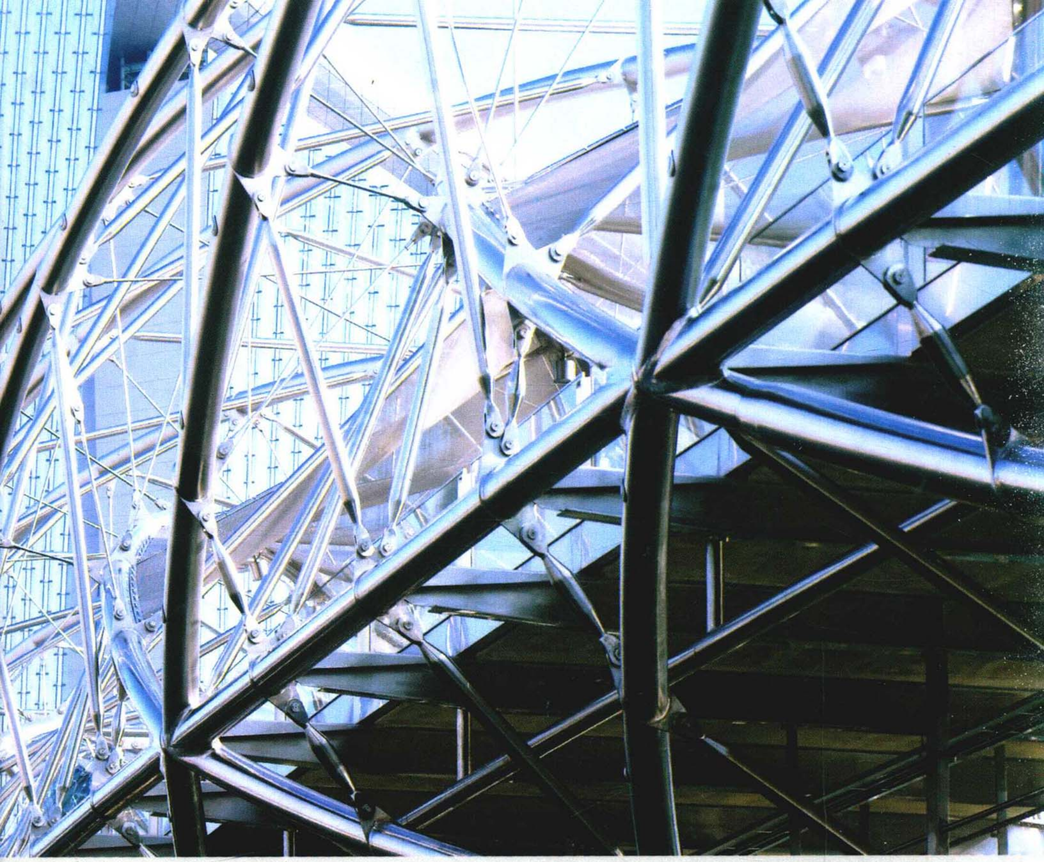

FINITE ELEMENT ANALYSIS AND DESIGN OF METAL STRUCTURES

EHAB ELLOBODY | RAN FENG | BEN YOUNG

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Finite Element Analysis and

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EHAB ELLOBODY

RAN FENG

BEN YOUNG

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Butterworth-Heinemann is an imprint of Elsevier
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress.

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

ISBN: 978-0-12-416561-8

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Visit our Web site at www.books.elsevier.com

13 14 15 16 17 10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

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CHAPTER 1

Introduction

1.1. GENERAL REMARKS

Most of finite element books available in the literature, e.g. Refs [1.1–1.7], deal with explanation of finite element method as a widely used numerical technique for solving problems in engineering and mathematical physics. The books mentioned in Refs [1.1–1.7] were written to provide basic learning tools for students in civil and mechanical engineering. The aforementioned books highlighted the general principles of finite element method and the application of method to solve practical problems. Numerous books are also available in the literature, as examples in Refs [1.8–1.26], addressing the behavior and design of metal structures. The books mentioned in Refs [1.8–1.26] have detailed the analysis and design of metal structural elements considering different design approaches. However, up-to-date, there is a dearth in the books that detail and highlight the implementation of finite element method in analyzing metal structures. Extensive numerical investigations using finite element method were presented in the literature as research papers on metal columns, beams, beam columns, and connections. However, detailed books that discuss the general steps of finite element method specifically as a complete work on metal structures and connections are rarely found in the literature, leading to the work presented in this book.

There are many problems and issues associated with modeling of metal structures in the literature that students, researchers, designers, and academics need to address. This book provides a collective material for the use of finite element method in understanding the behavior and structural performance of metal structures. Current design rules and specifications of metal structures are mainly based on experimental investigations, which are costly and time consuming. Hence, extensive numerical investigations were performed in the literature to generate more data, fill in the gaps, and compensate the lack of data. This book also highlights the use of finite element methods to improve and propose more accurate design guides for metal structures, which is rarely found in the literature. The book contains examples for finite element models developed for

Finite Element Analysis and Design of Metal Structures
DOI: http://dx.doi.org/10.1016/B978-0-12-416561-8.00001-9

different metal structures as well as worked design examples for metal structures. The authors hope that this book will provide the necessary material for all interested researchers in the field of metal structures. The book can also act as a useful teaching tool and help beginners in the field of finite element analysis of metal structures. The book can provide a robust approach for finite element analysis of metal structures that can be understood by undergraduate and postgraduate students.

The book consists of eight well-designed chapters covering necessary topics related to finite element analysis and design of metal structures. Chapter 1 provides a general background for the types of metal structures, mainly on columns, beams, and tubular connections. The three topics present the main structural components that form any metal frame, building, or construction. Detailing the analysis of these components would enable understanding the overall structural behavior of different metal structures. The chapter also gives a brief review of the role of experimental investigations as the basis for finite element analysis. Finally, the chapter highlights the importance of finite element modeling and current design codes for understanding the structural performance of metal structures.

Chapter 2 provides a simplified review of general steps of finite element analysis of metal structures. The chapter enables beginners to understand the fundamentals of finite element analysis and modeling of complicated structural behavior of metals. The chapter also includes how to divide a metal structural element into finite elements and how to select the best type of finite elements to represent the overall structural element. The chapter provides a brief review of the selection of displacement functions and definition of strain—displacement and stress—strain relationships. In addition, Chapter 2 also presents a brief review of the formation of element stiffness matrices and equations, the assemblage of these equations, and how the assembled equations are solved for unknowns.

Chapter 3 focuses on finite element modeling of metal structures and details the choice of element type and mesh size that can accurately simulate the complicated behavior of different metal structural elements. The chapter details how the nonlinear material behavior can be efficiently modeled and how the initial local and overall geometric imperfections were incorporated in the finite element analysis. Chapter 3 also details modeling of different loading and boundary conditions commonly applied to metal structures. The chapter focuses on the finite element modeling using any software or finite element package, as an example in this book, the use of ABAQUS [1.27] software in finite element modeling.

Chapter 4 extends the information covered in Chapter 3 to explain and detail the commonly used linear and nonlinear analyses in finite element modeling of metal structures. The chapter also explains the analyses generally used in any software and details as an example the linear and nonlinear analyses used by ABAQUS [1.27]. The chapter also contains a brief survey and background of the linear and nonlinear analyses. It details the linear eigenvalue used to model initial local and overall geometric imperfections. The nonlinear material and geometrical analyses related to metal structures are also highlighted in Chapter 4. In addition, the chapter also gives a detailed explanation for the RIKS method used in ABAQUS [1.27] that can accurately model the collapse behavior of metal structural elements.

Chapters 5–7 give illustrative examples for finite element models developed to understand the structural behavior of metal columns, beams, and tubular connections, respectively. These chapters start by a brief introduction to the contents as well as a detailed review on previous investigations on the subject. The chapters also detail the developed finite element models and the results obtained. The presented examples show the effectiveness of finite element models in providing detailed data that complement experimental data in the field. The results are discussed to show the significance of the finite element models in predicting the structural response of different metal structural elements.

Finally, Chapter 8 presents design examples for metal tubular connections. The chapter starts by a brief introduction to the contents. The chapter also details the finite element models developed for the presented metal tubular connections. The design rules specified in current codes of practice for the presented connections are also discussed and detailed in this chapter. At the end of the chapter, comparisons between design predictions and finite element results are presented.

1.2. TYPES OF METAL STRUCTURES

The main objective of this book is to provide a complete piece of work regarding finite element analysis of metal structures. Hence, it is decided to highlight finite element modeling of main metal structural elements, which are columns, beams, and tubular connections. The metal structures cover structures that may be constructed from any metal such as carbon steel, cold-formed steel, stainless steel, aluminum, or any other metals. The aforementioned materials have different stress–strain curves, yield, and post-yield criteria. Figure 1.1 shows examples of stress–strain curves

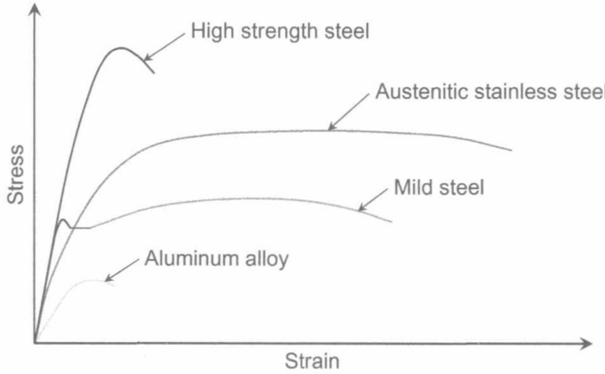

Figure 1.1 Stress–strain curves of different metals.

for some of the aforementioned metals. For example, the stress–strain curves of stainless steel, high strength steel, and aluminum have a rounded behavior with no yield plateau compared with the stress–strain curves of carbon steel as shown in Figure 1.1. Hence, the structural performance of these metal columns, beams, and tubular connections will be different from that of carbon steel. This book provides a detailed description on finite element analysis of columns, beams, and tubular connections that are composed of any metallic materials. It should also be noted that the structural performance of different metals varies at ambient temperature as well as at elevated temperatures. However, this book only focuses on analyzing metal structures at ambient temperature. Furthermore, the finite element analysis of metal structures depends on the type of applied loads. For example, the structural performance of metal structural elements subjected to static loads differs from that subjected to seismic, cyclic, dynamic loads or any other types of loads. However, this book details the finite element analysis of metal structures subjected to static loads or any other loads that can be replaced by equivalent static loads.

Looking at the metal columns analyzed using the finite element method in this book, the columns can be individual metal columns, which represent the cases of metal column test specimens. On the other hand, the columns investigated can be parts of structural metal frames or trusses. The columns presented in this book can have different end boundary conditions that vary from free to fixed-ended columns, different lengths, and different cross sections constructed from hot-rolled, cold-formed, or welded built-up sections. Figure 1.2 shows examples of different column cross sections that can be investigated using finite element

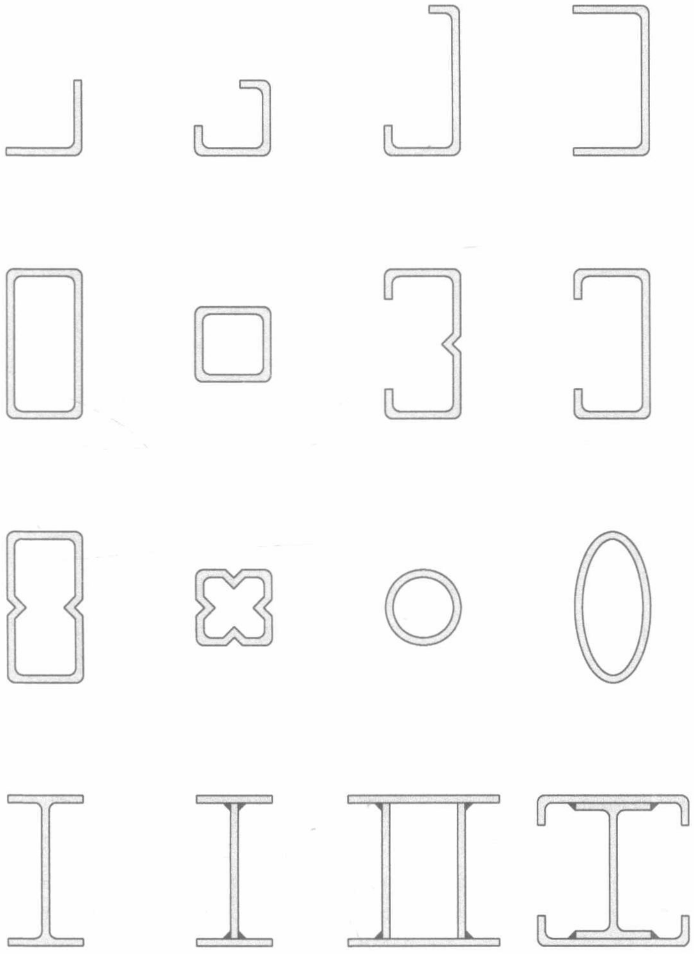

Figure 1.2 Cross sections of some metal columns covered in this book.

analysis covered in this book. The examples of cross sections are square, rectangular, circular, I-shaped, solid, hollow, stiffened, and unstiffened sections.

The metal beams presented in this book using the finite element method can also form single metal beams such as metal beam test specimens. Alternatively, the beams can be part of floor beams used in structural metal frames or framed trusses. Therefore, the beams investigated also can have different end boundary conditions that vary from free to fixed support with or without rigid and semi-rigid internal and end supports. The beams investigated can have different lengths and different

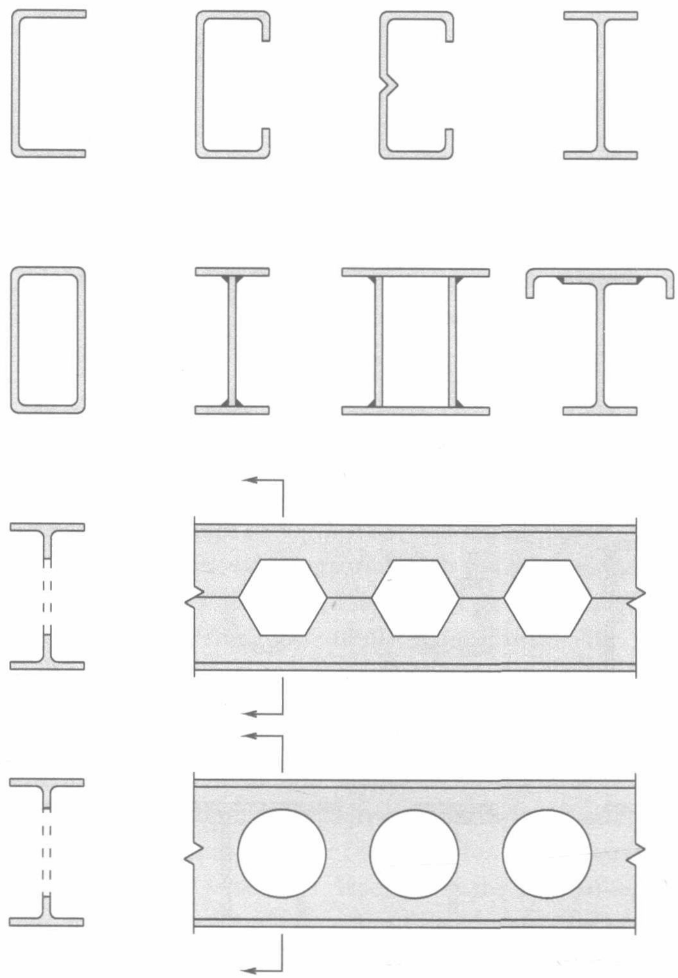

Figure 1.3 Cross sections of some metal beams covered in this book.

cross sections constructed from hot-rolled, cold-formed, or welded built-up sections. Figure 1.3 shows examples of different beam cross sections that can be investigated using finite element analysis. The examples of cross sections include I-shaped, channel, hollow, castellated, cellular, stiffened, and unstiffened sections, as shown in Figure 1.3.

Investigating the interaction between metal columns and beams using finite element analysis is also covered in this book. The beams and columns are the main supporting elements of any metal frames and trusses. By highlighting the structural performance of metal tubular connections,

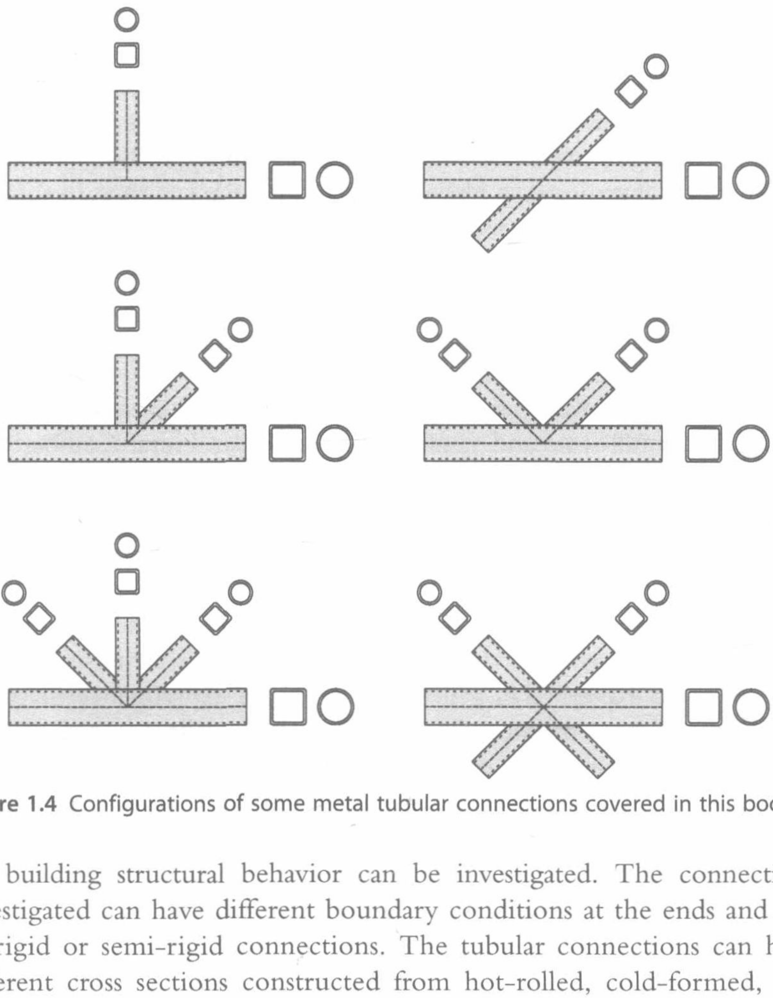

Figure 1.4 Configurations of some metal tubular connections covered in this book.

the building structural behavior can be investigated. The connections investigated can have different boundary conditions at the ends and can be rigid or semi-rigid connections. The tubular connections can have different cross sections constructed from hot-rolled, cold-formed, and welded sections. Figure 1.4 shows examples of different tubular connections that can be investigated using finite element analysis as detailed in this book. The tubular connections comprise square, rectangular, and circular hollow sections.

1.3. EXPERIMENTAL INVESTIGATIONS AND ITS ROLE FOR FINITE ELEMENT MODELING

Experimental investigation plays a major role in finite element analysis. It is important to verify and validate the accuracy of finite element models using test data, particularly nonlinear finite element models. In order to investigate the performance of a structural member, the member must be either tested in laboratory to observe the actual behavior or theoretically analyzed to obtain an exact closed-form solution. Getting an exact solution sometimes becomes very complicated and even impossible in some cases that involve highly nonlinear material and geometry analyses. However, experimental investigations are also costly and time consuming, which require specialized laboratory and expensive equipment as well as highly trained and skilled technician. Without the aforementioned requirements, the test data and results will not be accurate and will be misleading to finite element development. Therefore, accurate finite element models should be validated and calibrated against accurate test results.

Experimental investigations conducted on metal structures can be classified into full-scale and small-scale tests. In structural member tests, full-scale tests are conducted on members that have the same dimensions, material properties, and boundary conditions as that in actual buildings or constructions. On the other hand, small-scale tests are conducted on structural members that have dimensions less proportional to actual dimensions. The full-scale tests are more accurate without the size effect and provide more accurate data compared with small-scale tests; however, they are more expensive in general. Most of the experimental investigations carried out on metal structures are destructive tests in nature. This is attributed to the tests that are carried out until failure or collapse of the member in order to predict the capacity, failure mode, and overall structural member behavior. Tests must be very well planned and sufficiently instrumented to obtain required information. Efficient testing programs must investigate most of the parameters that affect the structural performance of tested specimens. The programs should also include some repeated tests to check the accuracy of the testing procedures. Experimentalists can efficiently plan the required number of tests, position, type, and number of instrumentations as well as significant parameters to be investigated.

Experimental investigations on metal structures are conducted to obtain required information from the tests using proper instrumentations and measurement devices. Although the explanation of various instrumentations and devices is not in the scope of this book, the required information for finite element analysis is highlighted herein. The required information can be classified into three main categories: initial data, material data, and data at the time of experiment. The initial data are obtained from test specimens prior to testing, such as the initial local and overall geometric imperfections, residual stresses, and dimensions of test specimens. The material data are conducted on tensile or compression coupon test specimens taken from untested specimens or material tests conducted on whole untested specimens, such as stub column tests, to determine the stress–strain curves of the materials. Knowing the stress–strain curves of materials provide the data regarding the yield stress, ultimate stress, strain at yield, strain at failure, ductility as well as initial modulus of elasticity. Finally, the data at the time of experiment provide the strength of structural test specimens, load–displacement relationships, load–strain relationships, and failure modes. The aforementioned data are examples of the main and commonly needed data for finite element analysis; however, the authors of this book recommend that each experimental investigation should be treated as an individual case and the data required have to be carefully studied to cover all parameters related to the tested structural element.

The tests conducted by Young and Lui [1.28,1.29] on cold-formed high strength stainless steel square and rectangular hollow section columns provided useful and required initial data, material data, and data at the time of experiment for development of finite element model. First, the tests have provided detailed data regarding initial local and overall geometric imperfections as well as residual stresses in the specimens, which represent "initial data." Second, the tests have provided detailed material properties for flat and corner portions of the sections, which represent "material data." Finally, the tests have provided detailed data on the compression column tests, which represent "test data at the time of experiment." Figure 1.5 shows the measured membrane residual stress distributions in cold-formed high strength stainless steel rectangular hollow section. The values of the residual stresses that are "material data" can be incorporated in the finite element model.

1.4. FINITE ELEMENT MODELING OF METAL STRUCTURES

Although extensive experimental investigations were presented in the literature on metal structures, the number of tests on some research topics is still limited. For example, up-to-date, the presented tests (Section 1.3) on cold-formed high strength stainless steel columns carried out by Young and Lui [1.28,1.29] remain pioneer in the field, and there is a lack of test data that highlight different parameters outside the scope of the presented experimental program [1.28,1.29]. The number of tests conducted on a

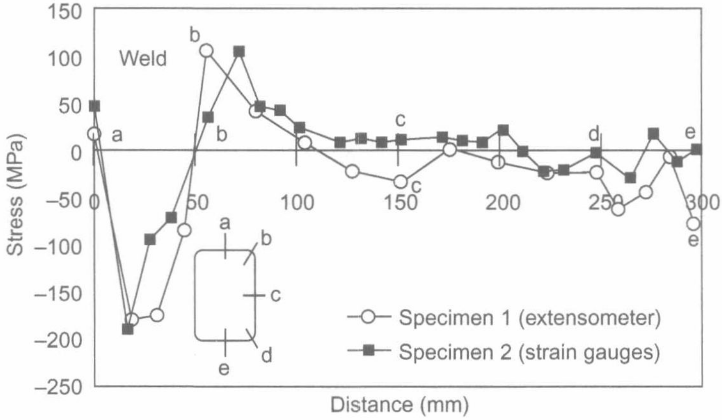

Figure 1.5 Measured membrane residual stress distributions in cold-formed high strength stainless steel tubular section [1.29].

specific research topic in the field of metal structures is limited by many factors. The factors comprise time, costs, labor, capacity of testing frame, capacity of loading jack, measurement equipment, and testing devices. Therefore, numerical investigations using finite element analysis were performed and found in the literature to compensate the lack of test data in the field of metal structures. However, detailed explanation on how successful finite element analysis can provide a good insight into the structural performance of metal structures was not fully addressed as a complete piece of work, which is credited to this book.

Following experimental investigations on metal structures, finite element analyses can be performed and verified against available test results. Successful finite element models are those that are validated against sufficient number of tests, preferably from different sources. Finite element modeling can be extended, once validated, to conduct parametric studies investigating the effects of the different parameters on the behavior and strength of metal structures. The analyses performed in the parametric studies must be well planned to predict the performance of the investigated structural elements outside the ranges covered in the experimental program. The parametric studies will generate more data that fill in the gaps of the test results. Hence, one of the advantages of the finite element modeling is to extrapolate the test data. However, the more significant advantage of finite element modeling is to clarify and explain the test data, which is credited to successful finite element models only. Successful finite element models can critically analyze test results and explain reasons behind failure of metal structures. The successful finite element models can go deeply in the test results to provide deformations, stresses, and strains at different locations in the test specimens, which is very difficult to be determined by instrumentation. The successful finite element models can save future tests in the studied research topic owing to that they can investigate different lengths, boundary conditions, cross sections, geometries, material strengths, and different loading.

As an example on how finite element analysis can generate more data to complement test results, the column tests conducted by Young and Lui [1.28,1.29] were modeled by Ellobody and Young [1.30]. The tested specimens were 15 square and rectangular hollow sections of cold-formed high strength stainless steel columns. The measured initial local and overall geometric imperfections and material nonlinearity of the flat and corner portions of the high strength stainless steel sections were carefully incorporated in the finite element model [1.30]. The column strengths and failure modes as well as the load-shortening curves of the columns were obtained using the finite element model. The validated finite element model [1.30] was used to perform parametric studies involving 42 new columns. The new columns investigated the effects of cross section geometries on the strength and behavior of cold-formed high strength stainless steel columns.

1.5. CURRENT DESIGN CODES

Design guides and specifications are proposed in different countries to define standards of metal structural sections, classification of sections, methods of analysis for structural members under different loading and boundary conditions, design procedures, material strengths, and factors of safety for designers and practitioners. The design guides are commonly based on experimental investigations. Many design formulas specified in current codes of practice are in the form of empirical equations proposed by experts in the field of metal structures. However, the empirical equations only provide guidance for design of metal structural elements in the ranges covered by the specifications. The ranges covered by the specification depend on the number of tests conducted on the metal structural elements at the time of proposing the codes. Since there are continuing progress in research to discover new materials, sections, connections, and different loading, the codes of practice need to update from time to time. Furthermore, test programs on metal structural elements are dependent on limits of the test specimens, loading, boundary conditions, and so on. Therefore, the design equations specified in current codes of practice always have limitations. Finite element analysis can provide a good insight into the behavior of metal structural elements outside the ranges covered by specifications. In addition, finite element analysis can check the validity of the empirical equations for sections affected by nonlinear material and geometry, which may be ignored in the specifications. Furthermore, design guides specified in current codes of practice contain some assumptions based on previous measurements, e.g., assuming values for initial local and overall imperfections in metal structural elements. Also, finite element modeling can investigate the validity of these assumptions. This book addresses the efficiency of finite element analyses, and the numerical results are able to improve design equations in the current codes of practice more accurately. However, it should be noted that there are many specifications developed all over the world for metal structures, such as steel structures, stainless steel structures, cold-formed steel structures, and aluminum structures. It is not the intension to include all these codes of practice in this book. Once again, this book focuses on finite element analysis. Therefore, the book only highlights the codes of practice related to the metal structures that performed finite element analysis.

As an example, the cold-formed high strength stainless steel columns tested by Young and Lui [1.28,1.29] and modeled by Ellobody and Young [1.30] as discussed in Sections 1.3 and 1.4, respectively, were assessed against the predications by the design codes of practice related to cold-formed stainless steel structures. The column test results [1.28,1.29] and finite element analysis results [1.30] were compared with design strengths calculated using the American [1.31], Australian/New Zealand [1.32], and European [1.33] specifications for cold-formed stainless steel structures. Based on the comparison between finite element analysis strengths and design strengths, it was concluded [1.30] that the design rules specified in the American, Australian/New Zealand, and European specifications are generally conservative for cold-formed high strength stainless steel square and rectangular hollow section columns, but unconservative for some of the short columns. It should be noted that this is an example on stainless steel columns only. The finite element analysis can be used to other metal structures. Subsequently, more numerical data can be generated and design equations in current codes of practice can be improved to cope with the advances in technology, materials, and constructions. Due to the advances in technology and materials, new construction