ADVANCED TOPICS IN SCIENCE AND TECHNOLOGY IN CHINA
国家科学技术学术著作出版基金资助出版

Guoqiang Li
Peijun Wang

Advanced Analysis and Design for Fire Safety of Steel Structures

ZHEJIANG UNIVERSITY PRESS
浙江大学出版社

Springer

国家科学技术学术著作出版基金资助项目

Guoqiang Li
Peijun Wang

Advanced Analysis and Design for Fire Safety of Steel Structures

With 254 figures

ZHEJIANG UNIVERSITY PRESS
浙江大学出版社

Springer

图书在版编目 (CIP) 数据

钢结构抗火高等分析与设计= Advanced Analysis and Design for Fire Safety of Steel Structures：英文 / 李国强，王培军著. —杭州：浙江大学出版社，2012.9
(中国科技进展丛书)
ISBN 978-7-308-08267-9

I. ①钢… II. ①李… ②王… III. ①钢结构—防火—结构设计—英文 IV. ①TU391.04

中国版本图书馆 CIP 数据核字(2012)第 207113 号

钢结构抗火高等分析与设计
李国强 王培军 著

责任编辑 尤建忠
封面设计 俞亚彤
出版发行 浙江大学出版社
网址：http://www.zjupress.com
Springer-Verlag GmbH
网址：http://www.springer.com
排 版 杭州理想广告有限公司
印 刷 浙江印刷集团有限公司
开 本 710mm×1000mm 1/16
印 张 23.25
字 数 718 千
版 印 次 2012 年 9 月第 1 版 2012 年 9 月第 1 次印刷
书 号 ISBN 978-7-308-08267-9 (浙江大学出版社)
ISBN 978-3-642-34392-6 (Springer-Verlag GmbH)
定 价 184.00 元

Preface

Advanced Analysis and Design for Fire Safety of Steel Structures presents a systematic description of recent research achievements on behaviors of structural steel components in a fire, such as the catenary actions of restrained steel beams, the design methods of restrained steel columns and the membrane actions of concrete floor slabs with steel decks in a fire. Using a systematic description of structural fire safety engineering principles, the authors illustrate the important difference between behaviors of isolated structural elements and restrained components in a global structure under fire conditions. The book is also essential for structural engineers who wish to improve their understanding of steel buildings exposed to fires. It is also an ideal textbook for introductory courses in fire safety for a master degree programme in structural engineering and a vital reading material for final year undergraduate students in civil engineering and fire safety engineering. Furthermore, it successfully bridges the information gap between fire safety engineers, structural engineers and building inspectors, and will be of significant interest to architects, code officials, building designers and fire fighters. We sincerely hope and anticipate that this book will be useful to anyone interested or involved in this fascinating and technologically important research area.

Since 1991 we have been devoted to the study of structural behaviors and analysis of steel structures in a fire. It is unimaginable that the work could have been carried out, year-by-year, without financial support. Therefore we gratefully acknowledge the National Natural Science Foundation of China (Grant Nos. 59478038, 59778032, 51008181), the National Natural Science Foundation of China for Distinguished Young Scholar (Grant No. 50225825), the Foundation for Innovative Research Groups of the National Natural Science Foundation of China (Grant Nos. 50321803, 50621062), the State Key Program of National Natural Science of China (Grant No. 50738005), the Joint Research Fund for Overseas Natural Science of China (Grant No. 50728805) and the Open Research Fund of the State Key Laboratory of Disaster Reduction in Civil Engineering (Grant No. SLDRCE09-TS-02) for the financial support.

It is indeed a great pleasure to extend our "thank you" to all our colleagues and former research students for their dedication to our research projects. Especially, the contributions to Chapter 2 from Dr. Yong Du, to Chapter 3 from Mr. Kai Chen and Dr. Guobiao Lou, to Chapter 7 from Dr. Shixiong Guo and Dr. Yinzhi Wang, to Chapter 8 from Dr. Weiyong Wang, to Chapter 9 from Dr. Shouchao Jiang and Ms. Nasi Zhang, to Chapter 10 from Dr. Shouchao Jiang and to Chapter 11 from Dr. Huangtin Zhou, Dr. Yong Du and Ms. Jueqian Huang. Their efforts are deeply appreciated and acknowledged. Finally, we would like to thank the editorial staff of Springer Verlag and Zhejiang University Press for their great assistance.

The authors
Shanghai, China
July, 2012

Contents

1

Introduction

1.1 Damage to Steel Structures Caused by Fire

Steel is a non-combustion material, but its yield strength and Young's modulus degrade quickly at high temperature, which makes the steel structure have a low fire resistance. At the temperature of 600 °C[1], the steel will lose most of its strength and stiffness. The fire in the building may cause global collapse to the steel structure or severe damage to structural components.

1.1.1 Global Collapse of Steel Structures in Fire

With the degrading of strength and stiffness of steel at elevated temperatures, structural components may lose their load bearing capacities, which lead to global collapse of the building. Fig. 1.1 illustrates a steel portal frame industrial building collapsed in a fire[2]. And the collapse of The World Trade Center is another disaster caused by fire[3].

1.1.2 Damage to Structural Components by Fire

In 1990, the Broadgate Street building had a fire during the construction phase and steel columns and steel beams were seriously damaged[4]. Fig. 1.2 illustrates the buckled steel column caused by the fire. Redistribution of the load to less severely heated components of the building leads to improved fire resistance performance of the structure.

In 2001, a severe fire happened at the Taipei Oriental Science District Building[2]. Though the overall structure of the building did not collapse, a large number of steel structural components were severely damaged. The damage to the steel structure included (a) fracture of the beam-to-column connection, (b) local buckling of the steel beam and (c) large deflection in the steel beam and the floor slab, as shown in Fig. 1.3.

1.2 Requirements for Fire Resistance of Steel Structures

Fire resistance is a measure of the ability of a building element to resist a fire. It is most often quantified as the time during which the element can meet certain criteria during exposure to a standard fire-resistance test. Structural fire resistance tests can also be quantified using the critical temperature or load bearing capacity of a structural element exposed to a fire.

1.2.1 Ultimate Limit State of Structures in a Fire

When a building is subjected to fire, the load bearing capacity of a structural component decreases with the elevation of the temperature. The ultimate limit state of the structure in the fire is reached when the load bearing capacity of the structural component equals the applied load.

Depending on whether the structure fails locally or globally, the ultimate limit states include failure of the structural component and failure of the complete structure.

Failure of the structural component [2] is identified as

- the structural component loses its stability;
- the deformation rate of the structural component exceeds a certain limit;
- the deformation of the structural component is not suitable for the load bearing function, which can be formulated as

$$\delta \geqslant \frac{l}{20} \tag{1.1}$$

The fire resistance test shows that when the character deformation rate of a structural component exceeds

Fig. 1.1 Collapse of an industrial building caused by fire

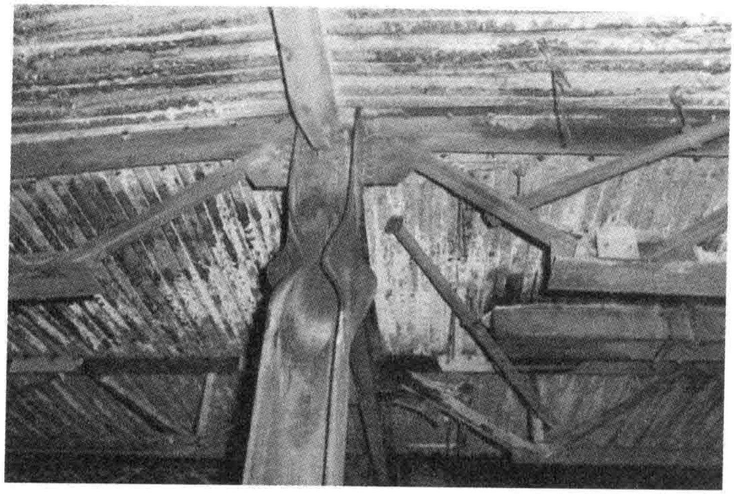
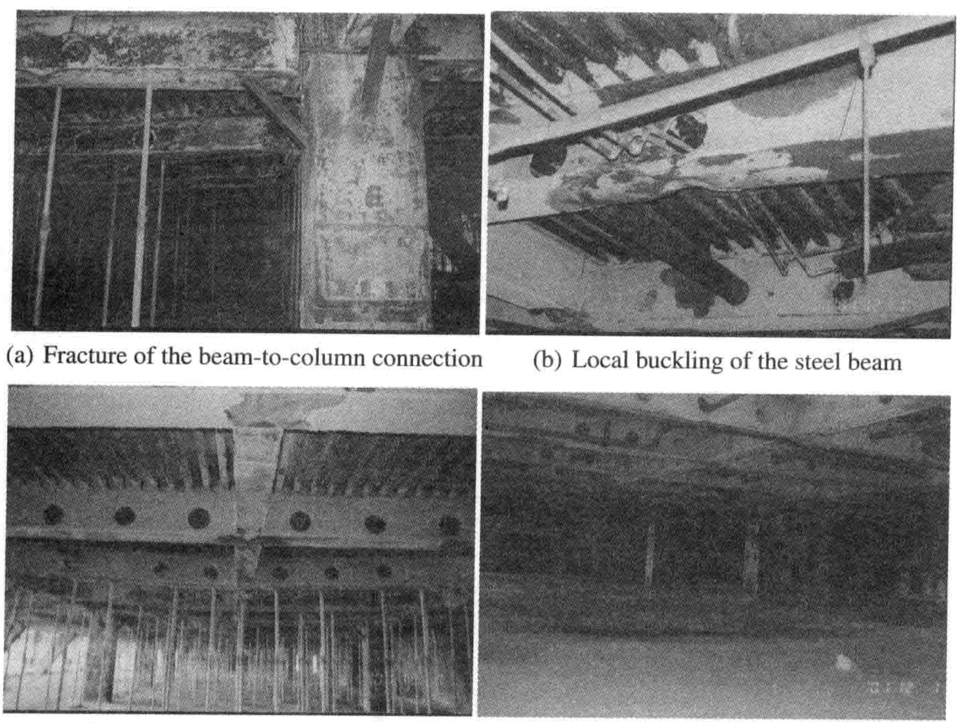


Fig. 1.2 Buckling of the column in a fire



(a) Fracture of the beam-to-column connection

(b) Local buckling of the steel beam

(c) Large deflection in the steel beam

(d) Large deflection in the floor slab

Fig. 1.3 Damage to the Taipei Oriental Science District Building caused by fire

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} \geqslant \frac{l^2}{15h_x} \tag{1.2}$$

the component will fail in a short time, where δ is the maximum deflection of the structural component in mm, as shown in Fig. 1.4.

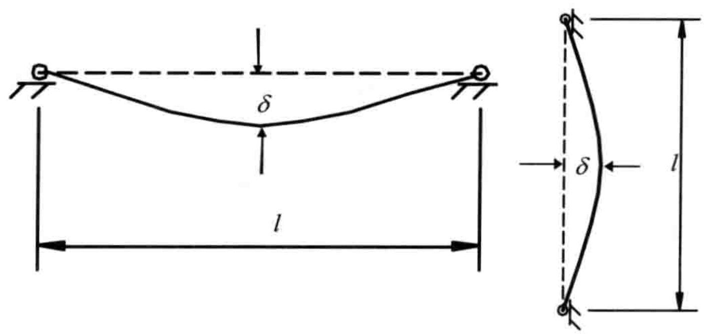


Fig. 1.4 Deformation of structural component in fire

Failure of the complete structure [2] is identified as

- the structure loses its overall stability;
- the deformation of the structure is not suitable for load bearing function, as shown in Fig. 1.5, which is formulated as

$$\frac{\delta}{h} \geqslant \frac{1}{30} \tag{1.3}$$

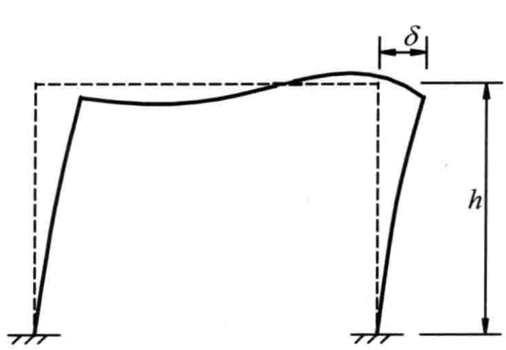


Fig. 1.5 Deformation of the structure in a fire

1.2.2 Load Bearing Capacity Criteria

The load bearing capacity criteria of the structural component or the overall structure in a fire is assessed on a calculation basis and can be expressed mathematically as follows using the limit state function, Z, which is defined as the algebraic difference between the structural capacity for fire-resistance and the corresponding demand. The load bearing capacity criteria can be expressed in one of the following three ways[1]

- on a time basis

$$Z = t_{fi,d} - t_{fi,req} \geqslant 0 \tag{1.4}$$

- on a strength basis

$$Z = R_{fi,d} - E_{fi,d} \geqslant 0 \tag{1.5}$$

- on a temperature basis

$$Z = T_{cr,d} - T_d \geqslant 0 \tag{1.6}$$

1.2.3 Fire-Resistance Duration Demands

The China Design Code on Building Fire Protection and Prevention (GB50016-2006)[5] gives the fire resistance duration demand for various structural components on a time basis, as listed in Table 1.1.

Table 1.1 Fire resistance of structural components

Type of structural component	Building grade for fire resistance (h)			
	Grade I	Grade II	Grade III	Grade IV
Fire resistance wall	3.00	3.00	3.00	3.00
Load bearing wall	3.00	2.50	2.00	0.50
Non-load bearing external wall	1.00	1.00	0.50	–
Stairway wall/ elevator wall	2.00	2.00	1.50	0.50
Partition wall between two residential cells	2.00	2.00	1.50	0.50
Partition wall along the evacuation route	1.00	1.00	0.50	0.25
Partition wall in a residential cell	0.75	0.50	0.50	0.25
Column	3.00	2.50	2.00	0.50
Beam	2.00	1.50	1.00	0.50
Slab	1.50	1.00	0.50	–
Roof load bearing structural component	1.50	1.00	–	–
Evacuation stair	1.50	1.00	0.50	–
Suspended ceiling (including the ceiling frame)	0.25	0.25	0.15	–

1.3 Approach for Determining Fire-Resistance of Steel Structures

The fire resistance of a steel structure can be obtained by experimental approach or analytical approach. Both of them have some advantages and disadvantages.

1.3.1 Experimental Approach

The standard fire resistance test is usually carried out to assign a fire resistance rating to a steel structure component to enable it to pass the regulatory fire resistance requirements. So far, numerous standard fire resistance tests for steel structural components have been carried out. In China it is GB/T 9978 [6] and in the United Kingdom it is the BS 476, Part 20 [7]. Other countries also have their own standards and all these standards are similar. For this reason, the fire exposure for the standard fire resistance test often uses an ISO standard [8].

The standard test for fire resistance of a structural element is carried out in a furnace, either gas or oil fired. The average rise in furnace temperature may accord to the following temperature-time relationship provided by ISO 834 [8] as

$$T - T_0 = 345\lg(8t + 1) \tag{1.7}$$

The fire resistance of a structural component can be assessed according to load bearing, insulation or integrity criteria [9]. The load bearing criterion is concerned with the load resistant capacity of the specimen. The insulation criterion is concerned with the excessive temperature increase on the unexposed surface of the specimen. And the integrity criterion is associated with the fire spreading through gaps in the test specimen. For a framed steel or steel-concrete composite component, the load bearing criterion is usually the major concern.

Although the standard fire resistance test is a convenient way to grade the relative fire performance of different types of structural members, for a number of reasons it is not very effective in developing our understanding of realistic structural behavior in a fire.

The main deficiencies in the standard fire resistance test are as follows [10]

- the standard fire exposure is only one of numerous types of realistic fire conditions;
- standard fire resistance tests are carried out on individual structural elements, not structural assemblies and the structural component interactions cannot be considered;
- standard fire resistance tests are carried out for very specific objectives and instrumentation is usually not adequate for thorough retrospective analysis;
- the boundary condition of the structural specimen under testing is usually simply supported, which is different from the condition of the element restrained in a real structure in most cases. However, any stiffness of this inevitable restraint could have a significant influence on the behavior of the element exposed to fire;
- the failure criteria usually do not adequately describe the intended usage of the building.