



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



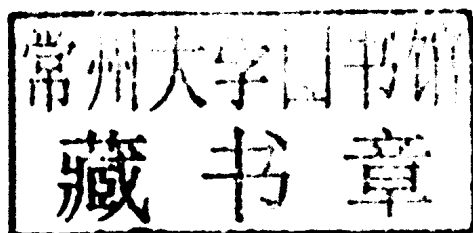
Springer

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

Not for sale outside Mainland of China

此书仅限中国大陆地区销售

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 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

版权所有 翻印必究 印装差错 负责调换

浙江大学出版社发行部邮购电话 (0571)88925591

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
1.1	Damage to Steel Structures Caused by Fire	1
1.1.1	Global Collapse of Steel Structures in Fire	1
1.1.2	Damage to Structural Components by Fire	1
1.2	Requirements for Fire Resistance of Steel Structures	2
1.2.1	Ultimate Limit State of Structures in a Fire	2
1.2.2	Load Bearing Capacity Criteria	5
1.2.3	Fire-Resistance Duration Demands	5
1.3	Approach for Determining Fire-Resistance of Steel Structures	6
1.3.1	Experimental Approach	6
1.3.2	Analytical Approach	7
	References	8
2	Fire in Buildings	11
2.1	Basic Concepts	11
2.1.1	Fire Load	11
2.1.2	Heat Released Rate	12
2.2	Compartment Fire	13
2.2.1	Development of Compartment Fire	13
2.2.2	Heat Release Model of Fire before Flashover	15
2.2.3	Conditions Necessary for Flashover	15
2.2.4	Heat Release Rate of the Fire after Flashover	16
2.2.5	Modeling of Compartment Fire	17
2.2.6	Empirical Modeling of Compartment Fire	18
2.3	Large Space Building Fire	22
2.3.1	Characteristics of Large Space Building	22
2.3.2	Characteristics of Large Space Building Fire	22
2.3.3	Simulation of Large Space Building Fire using Zone Model	23
2.3.4	Characteristics of Large Space Building Fire	27
2.4	Standard Fire and Equivalent Exposure Time	31
2.4.1	Standard Fire	31

2.4.2	Equivalent Exposure Time	32
References	.....	34
3	Properties of Steel at Elevated Temperatures	37
3.1	Thermal Properties of Structural Steel at Elevated Temperatures ...	37
3.1.1	Conductivity	37
3.1.2	Specific Heat	38
3.1.3	Density	39
3.2	Mechanical Properties of Structural Steel at High Temperature.....	40
3.2.1	Test Regimes	40
3.2.2	Definition of Yield Strength at High Temperature	41
3.2.3	Mechanical Properties of Structural Steel at High Temperatures	42
3.2.4	Yield Strength and Elastic Modulus of Fire-Resistant Steel at High Temperatures	43
3.2.5	Stress-Strain Relationship of Normal Strength Structural Steel and Fire-Resistant Steel at Elevated Temperatures ...	48
3.3	Mechanical Properties of High Strength Steel at High Temperatures	48
3.3.1	High Strength Bolt	48
3.3.2	High Strength Cable	50
3.4	Properties of Stainless Steel at High Temperatures	54
3.4.1	Thermal Properties of Stainless Steel	54
3.4.2	Mechanical Properties of Stainless Steel at High Temperatures	54
References	.....	64
4	Temperature Elevations of Structural Steel Components Exposed to Fire	67
4.1	Laws of Heat Transfer	67
4.1.1	Heat Transfer in Structural Members	67
4.1.2	Heat Transfer between Hot Smoke and a Structural Member	68
4.2	Practical Calculation Method for Temperature Elevation of Structural Members	69
4.2.1	Calculating Model	69
4.2.2	Temperature Elevation of Structural Component with Uniformly Distributed Temperature	70
4.2.3	Temperature of Structural Component with Non-Uniformly Distributed Temperature	79
4.3	Practical Calculation Method for Temperature Evolution of Structural Members Exposed to a Large Space Building Fire	79
4.3.1	Effects of Flame Radiation on Temperature Elevation of Un-Protected Steel Structural Components	80
4.3.2	Parametric Study	86
4.3.3	Limit Value of Flame Radiation	88
4.4	Example	89
References	.....	90

5	Fire-Resistance of Isolated Flexural Structural Components	93
5.1	Load-bearing Capacity of a Flexural Steel Component at High Temperatures	93
5.1.1	Strength of a Flexural Steel Component at High Temperatures.	93
5.1.2	Lateral Torsional Buckling Strength of a Flexural Steel Component at High Temperatures	93
5.1.3	Critical Temperature of a Flexural Steel Component in Fire	95
5.1.4	Example.	96
5.2	Fire-resistance of Flexural Steel-Concrete Composite Components	99
5.2.1	Material Properties and Temperature Calculation of a Composite Beam	99
5.2.2	Strength of a Composite Beam at High Temperature	100
5.2.3	Critical Temperature of a Composite Beam	101
5.2.4	Parametric Study	102
5.2.5	Simplified Approach for the Fire Resistance Design of Composite Beams	106
5.2.6	Example and Comparison	108
5.2.7	Experimental Validation	110
	References	113
6	Fire-Resistance of Isolated Compressed Steel Components	115
6.1	Fire Resistance of Axially Compressed Steel Components	115
6.1.1	Load Bearing Capacity of Axially Compressed Steel Components	115
6.1.2	Critical Temperature of an Axially Compressed Component	119
6.1.3	Example.	119
6.2	Design Method for a Structural Component under the Combined Axial Force and Bending Moment	122
6.2.1	Stability of a Structural Component under the Combined Axial Force and Bending Moment	122
6.2.2	Cross-Sectional Strength of the Structural Component under the Combined Axial Force and Bending Moment at Elevated Temperatures	123
6.2.3	Critical Temperature of the Structural Component Subjected to the Combined Axial Force and Bending Moment	123
6.2.4	Example.	125
	References	129
7	Fire-Resistance of Restrained Flexural Steel Components	131
7.1	Fire-Resistance of a Restrained Steel Beam	131
7.1.1	Fire Test of Restrained Steel Beams	132
7.1.2	Analysis and Design for Fire-Resistance of a Restrained Steel Beam	143

7.2	Fire Resistance of Steel-Concrete Composite Beams	159
7.2.1	Fire Test on Restrained Steel-Concrete Composite Beams ..	159
7.2.2	Analysis of Restrained Steel-Concrete Composite Beams ...	169
7.2.3	Practical Design Method for a Restrained Steel-Concrete Composite Beam	176
7.2.4	Axial Force in the Composite Beam.....	178
	References	184
8	Fire-Resistance of Restrained Steel Columns	189
8.1	Fire Test on Restrained Steel Columns with Axial and Rotational Restraint	189
8.1.1	Test Set-Up and Test Specimen.....	190
8.1.2	Displacement and Temperature Acquisition	192
8.1.3	Test Schedule	193
8.1.4	Test Results	193
8.1.5	Numerical Simulation of the Fire Test	200
8.2	Parametric Study of Restrained Steel Columns in a Fire	202
8.2.1	Parameters	204
8.2.2	Parametric Study on a Restrained Steel Column under Axial Load Only in a Fire	206
8.2.3	Parametric Study of a Restrained Column under Combined Axial Load and Bending Moment in a Fire	207
8.3	Simplified Design Method for Restrained Steel Columns in a Fire ..	214
8.3.1	Design Method for Restrained Columns under Axial Load Only in a Fire	217
8.3.2	Design Methods for the Restrained Columns under Combined Axial Load and Bending Moment	222
8.4	Fire-Resistance of Restrained Columns with Non-Uniform Temperature Distribution	231
8.4.1	Test Arrangement and Instrumentation	232
8.4.2	Temperature Distribution.....	233
8.4.3	Continuum Model	234
8.4.4	Experiment Study	238
	References	241
9	Fire-Resistance of Composite Concrete Slabs	245
9.1	Fire-resistance Design Method for Composite Concrete Slabs Based on Small Deflection Theory	245
9.1.1	Studied Slabs	245
9.1.2	Parametric Studies	247
9.1.3	Simplified Design Method.....	250
9.1.4	Verification by the Fire Resistance Test	252
9.2	Fire Resistance Design Method for the Composite Slab Considering Membrane Action	252

9.2.1	Development of the Membrane Action of a Composite Slab in a Fire	252
9.2.2	Fire Test on the Composite Slab	256
9.2.3	Analysis of the Composite Slab in Consideration of the Membrane Action in a Fire	268
References	.....	279
10	Analysis of Steel Moment-Resistant Frames Subjected to a Fire	281
10.1	Element for Analysis	282
10.1.1	Properties of the Elemental Cross-Section	282
10.1.2	Location of the Neutral Axis in an Elastic State	283
10.1.3	Equivalent Axial Stiffness	283
10.1.4	Equivalent Bending Stiffness in an Elastic State	284
10.1.5	Initial Yielding Moment	284
10.1.6	Location of the Neutral Axis in Total Plastic State	284
10.1.7	Plastic Moment	285
10.1.8	Stiffness of Element	285
10.2	Thermal Force of Element	287
10.3	Structural Analysis	287
10.4	Experimental and Theoretical Prediction	290
References	.....	297
11	Analysis and Design of Large Space Steel Structure Buildings Subjected to a Fire	299
11.1	Practical Analysis Approach for Steel Portal Frames in a Fire	299
11.1.1	Finite Element Modeling and Assumptions	299
11.1.2	Parameters Influencing the Fire Resistance of a Steel Portal Frame	301
11.1.3	Estimation of the Critical Temperature of a Steel Portal Frame	305
11.1.4	Example	308
11.1.5	Fire Protection	309
11.2	Critical Temperature of a Square Pyramid Grid Structure in a Fire ..	309
11.2.1	Parameters of Grid Structures	309
11.2.2	Definition of Parameters	310
11.2.3	Critical Temperature of the Structural Component	312
11.2.4	Critical Temperature of the Grid Structure in Uniform Temperature Field	312
11.2.5	Critical Temperatures of the Grid Structure in a Non-Uniform Temperature Field	314
11.2.6	Conditions for a Grid Structure with no Need of Fire Protection	316
11.3	Continuous Approach for Cable-Net Structural Analysis in a Fire ..	316
11.3.1	Behavior of a Single Cable in a Fire	317
11.3.2	Behavior of the Cable-Net Structure in a Fire	323

11.3.3	Simplified Method for the Critical Temperature of a Cable-Net Structure	327
11.3.4	Critical Temperature of a Cable-Net Structure with Elliptical or Diamond Plan View	329
11.3.5	Critical Temperature of the Cable-Net Structure with Parabolic Plan View	329
	References	331
	Appendix A: Parameters for Calculating the Smoke Temperature in Large Space Building Fire	333
	Appendix B: Stiffness Matrixes of Beam-Column Elements	341
	Appendix C: Height of the Flame	343
	Appendix D: Critical Temperatures of Composite Beams	345
	Appendix E: Critical Temperatures of a Steel Column Subjected to Combined Axial Force and Bending Moment	349
	Appendix F: Maximum Fire Power at Which a Grid Structure Does not Need Fire Protection	351
	Index	355

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

$$\delta \geq \frac{l}{20} \quad (1.1)$$

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

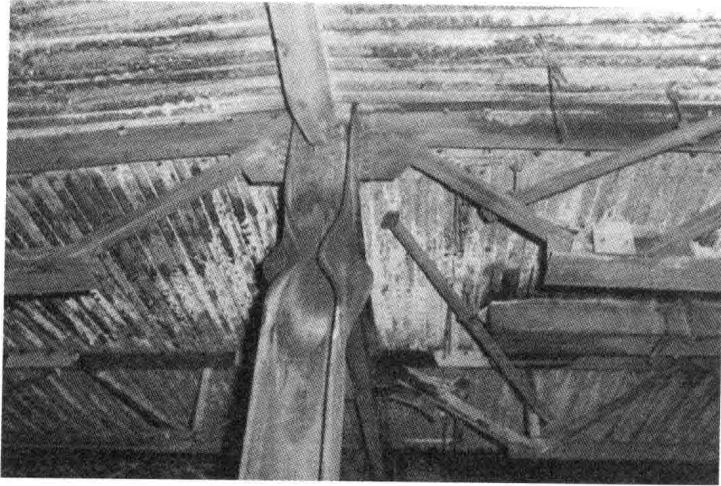
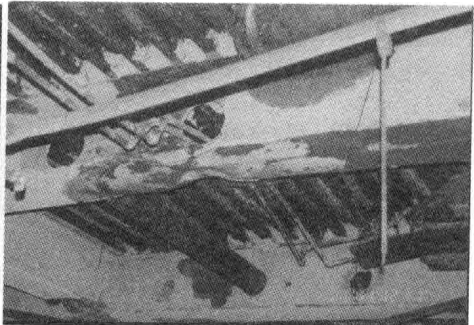
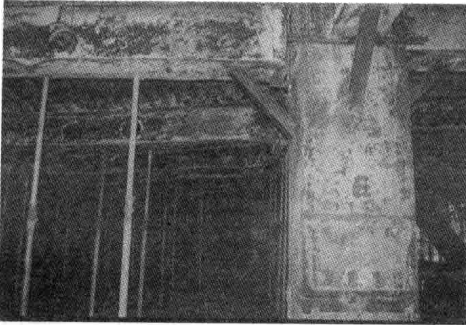


Fig. 1.2 Buckling of the column in a fire



(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

$$\frac{d\delta}{dt} \geq \frac{l^2}{15h_x} \quad (1.2)$$

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.

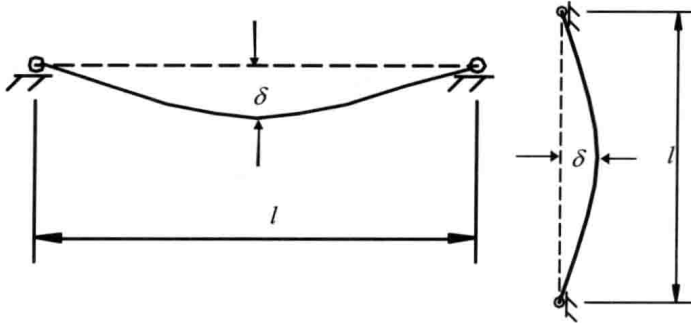


Fig. 1.4 Deformation of structural component in fire

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

$$\frac{\delta}{h} \geq \frac{1}{30} \quad (1.3)$$

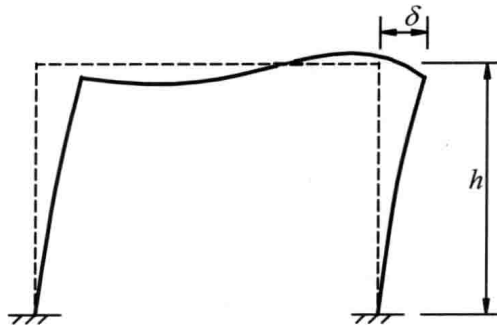


Fig. 1.5 Deformation of the structure in a fire

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

$$Z = t_{fi,d} - t_{fi,req} \geq 0 \quad (1.4)$$

- on a strength basis

$$Z = R_{fi,d} - E_{fi,d} \geq 0 \quad (1.5)$$

- on a temperature basis

$$Z = T_{cr,d} - T_d \geq 0 \quad (1.6)$$

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

$$T - T_0 = 345 \lg(8t + 1) \quad (1.7)$$

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.