# Contents

Preface xv
List of Notations xvi

1 Introduction 1
   1.1 Objective and Target Audience 1
   1.2 Fire Safety 2
   1.3 Performance-based Design 2
      1.3.1 Fundamentals of Performance-based Design 2
      1.3.2 Documentation and Quality Control 4
      1.3.3 Risk Assessment 4
   1.4 Structural Fire Engineering 5
   1.5 Purpose of this Book 5
   1.6 Units 6
   1.7 Organization of Chapters 6

2 Fire Safety in Buildings 8
   2.1 Fire Safety Objectives 8
      2.1.1 Life Safety 8
      2.1.2 Property Protection 9
      2.1.3 Environmental Protection 9
   2.2 Process of Fire Development 9
      2.2.1 Fire Behaviour 10
      2.2.2 Human Behaviour 11
      2.2.3 Fire Detection 12
      2.2.4 Active Control 12
      2.2.5 Passive Control 12
   2.3 Conceptual Framework for Fire Safety 13
      2.3.1 Scenario Analysis 13
      2.3.2 Quantitative Risk Assessment 13
      2.3.3 Fire Safety Concepts Tree 14
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>Fire Resistance</td>
<td>17</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Examples of Fire Resistance</td>
<td>17</td>
</tr>
<tr>
<td>2.4.2</td>
<td>Objectives for Fire Resistance</td>
<td>19</td>
</tr>
<tr>
<td>2.4.3</td>
<td>Fire Design Time</td>
<td>20</td>
</tr>
<tr>
<td>2.4.4</td>
<td>Trade-offs</td>
<td>21</td>
</tr>
<tr>
<td>2.4.5</td>
<td>Repairability and Reserviceability</td>
<td>22</td>
</tr>
<tr>
<td>2.5</td>
<td>Controlling Fire Spread</td>
<td>22</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Fire Spread within Room of Origin</td>
<td>22</td>
</tr>
<tr>
<td>2.5.2</td>
<td>Fire Spread to Adjacent Rooms</td>
<td>23</td>
</tr>
<tr>
<td>2.5.3</td>
<td>Fire Spread to Other Storeys</td>
<td>25</td>
</tr>
<tr>
<td>2.5.4</td>
<td>Fire Spread to Other Buildings</td>
<td>27</td>
</tr>
<tr>
<td>2.6</td>
<td>Building Construction for Fire Safety</td>
<td>29</td>
</tr>
<tr>
<td>2.6.1</td>
<td>Fire during Construction and Alterations</td>
<td>29</td>
</tr>
<tr>
<td>2.6.2</td>
<td>Fire following Earthquake</td>
<td>30</td>
</tr>
<tr>
<td>2.7</td>
<td>Assessment and Repair of Fire Damage</td>
<td>31</td>
</tr>
<tr>
<td>2.7.1</td>
<td>Inspection</td>
<td>32</td>
</tr>
<tr>
<td>2.7.2</td>
<td>Steel</td>
<td>32</td>
</tr>
<tr>
<td>2.7.3</td>
<td>Concrete and Masonry</td>
<td>33</td>
</tr>
<tr>
<td>2.7.4</td>
<td>Timber</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>Fires and Heat</td>
<td>35</td>
</tr>
<tr>
<td>3.1</td>
<td>Fires in General</td>
<td>35</td>
</tr>
<tr>
<td>3.2</td>
<td>Combustion</td>
<td>37</td>
</tr>
<tr>
<td>3.3</td>
<td>Fire Initiation</td>
<td>39</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Sources and Mechanisms</td>
<td>39</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Pilot Ignition and Auto-ignition</td>
<td>39</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Flame Spread</td>
<td>39</td>
</tr>
<tr>
<td>3.4</td>
<td>Pre-flashover Fires</td>
<td>40</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Burning Items in Open Air</td>
<td>40</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Burning Items in Rooms</td>
<td>42</td>
</tr>
<tr>
<td>3.4.3</td>
<td>t-Squared Fires</td>
<td>44</td>
</tr>
<tr>
<td>3.4.4</td>
<td>Fire Spread to Other Items</td>
<td>46</td>
</tr>
<tr>
<td>3.4.5</td>
<td>Pre-flashover Fire Calculations</td>
<td>46</td>
</tr>
<tr>
<td>3.5</td>
<td>Flashover</td>
<td>48</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Conditions Necessary for Flashover</td>
<td>48</td>
</tr>
<tr>
<td>3.6</td>
<td>Post-flashover Fires</td>
<td>49</td>
</tr>
<tr>
<td>3.6.1</td>
<td>Ventilation Controlled Burning</td>
<td>49</td>
</tr>
<tr>
<td>3.6.2</td>
<td>Fuel Controlled Burning</td>
<td>53</td>
</tr>
<tr>
<td>3.6.3</td>
<td>Fire Temperatures</td>
<td>54</td>
</tr>
<tr>
<td>3.6.4</td>
<td>Computer Models</td>
<td>58</td>
</tr>
<tr>
<td>3.7</td>
<td>Design Fires</td>
<td>60</td>
</tr>
<tr>
<td>3.7.1</td>
<td>Hand Methods</td>
<td>60</td>
</tr>
<tr>
<td>3.7.2</td>
<td>Published Curves</td>
<td>61</td>
</tr>
<tr>
<td>3.7.3</td>
<td>Eurocode Parametric Fires</td>
<td>62</td>
</tr>
</tbody>
</table>
3.8 Other Factors 66
3.8.1 Additional Ventilation Openings 66
3.8.2 Progressive Burning 66
3.8.3 Localized Fires 69
3.9 Heat Transfer 69
3.9.1 Conduction 69
3.9.2 Convection 72
3.9.3 Radiation 72
3.9.4 Design Charts for Fire Resistance Calculation 74
3.10 Worked Examples 75

4 Fire Severity and Fire Resistance 84
4.1 Providing Fire Resistance 84
4.1.1 Background 84
4.1.2 Fire Exposure Models 88
4.1.3 Design Combinations 89
4.2 Fire Severity 89
4.3 Equivalent Fire Severity 90
4.3.1 Equal Area Concept 90
4.3.2 Maximum Temperature Concept 91
4.3.3 Minimum Load Capacity Concept 92
4.3.4 Time Equivalent Formulae 92
4.4 Fire Resistance 95
4.4.1 Definition 95
4.4.2 Assessing Fire Resistance 95
4.5 Fire Resistance Tests 96
4.5.1 Standards 96
4.5.2 Test Equipment 97
4.5.3 Failure Criteria 97
4.5.4 Standard of Construction 101
4.5.5 Furnace Pressure 101
4.5.6 Applied Loads 101
4.5.7 Restraint and Continuity 102
4.5.8 Small-scale Furnaces 103
4.6 Specifying Fire Resistance 103
4.6.1 Approved Fire Resistance Ratings 103
4.6.2 Fire Resistance by Calculation 104
4.7 Fire Resistance of Assemblies 107
4.7.1 Walls 107
4.7.2 Floors 108
4.7.3 Beams 108
4.7.4 Columns 108
4.7.5 Penetrations 109
4.7.6 Junctions and Gaps 110
4.7.7 Seismic Gaps 110
4.7.8 Fire Doors 110
4.7.9 Ducts 111
4.7.10 Glass 112
4.7.11 Historical Buildings 112
4.8 Worked Examples 113

5 Design of Structures Exposed to Fire 115
5.1 Structural Design at Normal Temperatures 115
5.2 Loads 116
  5.2.1 Types of Load 116
  5.2.2 Load Combinations 116
  5.2.3 Structural Analysis 116
  5.2.4 Non-linear Analysis 117
  5.2.5 Design Format 117
  5.2.6 Working Stress Design Format 118
  5.2.7 Ultimate Strength Design Format 119
  5.2.8 Material Properties 120
  5.2.9 Probability of Failure 121
5.3 Structural Design in Fire Conditions 122
  5.3.1 Design Equation 123
  5.3.2 Loads for Fire Design 124
  5.3.3 Structural Analysis for Fire Design 125
5.4 Material Properties in Fire 126
  5.4.1 Testing Regimes 126
  5.4.2 Components of Strain 127
5.5 Design of Individual Members Exposed to Fire 130
  5.5.1 Tension Members 130
  5.5.2 Compression Members 130
  5.5.3 Beams 131
5.6 Design of Structural Assemblies Exposed to Fire 135
  5.6.1 Frames 135
  5.6.2 Redundancy 135
  5.6.3 Disproportionate Collapse 136
  5.6.4 Continuity 136
  5.6.5 Plastic Design 142
  5.6.6 Axial Restraint 143
  5.6.7 After-fire Stability 149
5.7 Worked Examples 149

6 Steel Structures 154
6.1 Behaviour of Steel Structures in Fire 154
  6.1.1 Structural Steel Design Process 155
6.2 Steel Temperature Prediction 157
  6.2.1 Fire Exposure 157
  6.2.2 Calculation Methods 158
  6.2.3 Section Factor 158
  6.2.4 Thermal Properties 159
  6.2.5 Temperature Calculation for Unprotected Steelwork 161
  6.2.6 Temperature Calculation for Protected Steelwork 163
  6.2.7 Typical Steel Temperatures 164
  6.2.8 Temperature Calculation for External Steelwork 165
6.3 Protection Systems 166
  6.3.1 Concrete Encasement 167
  6.3.2 Board Systems 167
  6.3.3 Spray-on Systems 169
  6.3.4 Intumescent Paint 169
  6.3.5 Protection with Timber 170
  6.3.6 Concrete Filling 170
  6.3.7 Water Filling 171
  6.3.8 Flame Shields 171
6.4 Mechanical Properties of Steel at Elevated Temperature 171
  6.4.1 Components of Strain 171
  6.4.2 Thermal Strain 172
  6.4.3 Creep Strain 173
  6.4.4 Stress-related Strain 174
  6.4.5 Proof Strength and Yield Strength 174
  6.4.6 Design Values 175
  6.4.7 Modulus of Elasticity 178
  6.4.8 Residual Stresses 179
6.5 Design of Steel Members Exposed to Fire 179
  6.5.1 Design Methods 179
  6.5.2 Design of Steel Tensile Members 180
  6.5.3 Design of Simply Supported Steel Beams 181
  6.5.4 Lateral-torsional Buckling 184
  6.5.5 Design for Shear 184
  6.5.6 Continuous Steel Beams 185
  6.5.7 Steel Columns 186
6.6 Bolted and Welded Connections 187
6.7 Cast-iron Members 188
6.8 Design of Steel Buildings Exposed to Fire 188
6.9 Worked Examples 188

7 Concrete Structures 195
  7.1 Behaviour of Concrete Structures in Fire 195
  7.2 Concrete Materials in Fire 196
    7.2.1 Normal Weight Concrete 196
| 7.2.2  High Strength Concrete          | 196 |
| 7.2.3  Lightweight Concrete           | 198 |
| 7.2.4  Steel-fibre Reinforced Concrete| 199 |
| 7.2.5  Masonry                        | 199 |
| 7.2.6  Prestressed Concrete           | 199 |
| 7.2.7  External Reinforcing           | 200 |
| 7.3    Spalling of Cover Concrete     | 201 |
| 7.3.1  Cover                          | 201 |
| 7.3.2  Spalling                       | 201 |
| 7.4    Concrete and Steel Reinforcing Temperatures | 202 |
| 7.4.1  Fire Exposure                  | 202 |
| 7.4.2  Calculation Methods            | 202 |
| 7.4.3  Thermal Properties             | 204 |
| 7.5    Mechanical Properties of Concrete at Elevated Temperatures | 207 |
| 7.5.1  Test Methods                   | 207 |
| 7.5.2  Components of Strain           | 207 |
| 7.5.3  Thermal Strain                 | 208 |
| 7.5.4  Creep Strain and Transient Strain | 209 |
| 7.5.5  Stress Related Strain          | 209 |
| 7.6    Design of Concrete Members Exposed to Fire | 213 |
| 7.6.1  Member Design                  | 215 |
| 7.6.2  Simply Supported Concrete Slabs and Beams | 215 |
| 7.6.3  Shear Strength                 | 217 |
| 7.6.4  Continuous Slabs and Beams     | 218 |
| 7.6.5  Axial Restraint                | 220 |
| 7.6.6  Reinforced Concrete Columns    | 223 |
| 7.6.7  Reinforced Concrete Walls      | 223 |
| 7.6.8  Reinforced Concrete Frames     | 224 |
| 7.7    Worked Examples                | 224 |
| 8      Composite Structures          | 234 |
| 8.1    Fire Resistance of Composite Elements | 234 |
| 8.2    Assessing Fire Resistance      | 237 |
| 8.2.1  Tabulated Data for Beams and Columns | 237 |
| 8.2.2  Simple Calculation Methods     | 237 |
| 8.2.3  Advanced Calculation Methods   | 238 |
| 8.3    Behaviour and Design of Individual Composite Members in Fire | 238 |
| 8.3.1  Composite Slabs                | 238 |
| 8.3.2  Composite Beams                | 240 |
| 8.3.3  Composite Columns              | 243 |
| 8.4    Design of Steel and Composite Buildings Exposed to Fire | 248 |
| 8.4.1  Multi-storey Steel Frame Buildings | 248 |
| 8.4.2  Car Parking Buildings          | 251 |
| 8.4.3  Single-storey Portal Frame Buildings | 252 |
| 8.5    Worked Example                 | 255 |
9 Timber Structures

9.1 Description of Timber Construction
9.1.1 Heavy Timber Construction
9.1.2 Laminated Timber
9.1.3 Behaviour of Timber Structures in Fire
9.1.4 Fire Resistance Ratings
9.1.5 Fire Retardant Treatments

9.2 Wood Temperatures
9.2.1 Temperatures Below the Char
9.2.2 Thermal Properties of Wood

9.3 Mechanical Properties of Wood
9.3.1 Mechanical Properties of Wood at Normal Temperatures
9.3.2 Mechanical Properties of Wood at Elevated Temperatures

9.4 Charring Rate
9.4.1 Overview of Charring
9.4.2 Corner Rounding
9.4.3 Charring Rate of Protected Timber
9.4.4 Effect of Heated Wood Below the Char Line
9.4.5 Design for Realistic Fires

9.5 Design for Fire Resistance of Heavy Timber Members
9.5.1 Design Concepts
9.5.2 Timber Beams
9.5.3 Timber Tensile Members
9.5.4 Timber Columns
9.5.5 Empirical Equations
9.5.6 Timber Beam-columns
9.5.7 Timber Decking
9.5.8 Hollow Core Timber Floors
9.5.9 Timber-concrete Composite Floors
9.5.10 Cross Laminated Timber
9.5.11 Reinforced Glulam Timber
9.5.12 Post-tensioned Timber Structures

9.6 Timber Connections in Fire
9.6.1 Geometry of Timber Connections
9.6.2 Steel Dowel-type Fasteners
9.6.3 Connections with Side Members of Wood
9.6.4 Connections with External Steel Plates
9.6.5 Glued Timber Connections

9.7 Worked Examples

10 Light Frame Construction

10.1 Summary of Light Frame Construction
10.2 Gypsum Plaster Board
10.2.1 Manufacture
10.2.2 Types of Gypsum Board 305
10.2.3 Chemistry 306
10.2.4 Thermal Properties 306
10.2.5 Fire Resistance 306
10.2.6 Ablation 308
10.2.7 Cavity Insulation 308

10.3 Fire Behaviour 309
10.3.1 Walls 310
10.3.2 Floors 310
10.3.3 Buildings 310

10.4 Fire Resistance Ratings 311
10.4.1 Failure Criteria 311
10.4.2 Listings 312
10.4.3 Generic Ratings 312
10.4.4 Proprietary Ratings 312
10.4.5 Typical Fire Resistance Ratings 312
10.4.6 Fire Severity 313

10.5 Design for Separating Function 314
10.5.1 Temperatures Within Light Frame Assemblies 314
10.5.2 Insulation 315
10.5.3 Component Additive Methods 316
10.5.4 Finite Element Calculations 317

10.6 Design for Load-bearing Capacity 318
10.6.1 Verification Methods 318
10.6.2 Calculation Methods 318
10.6.3 Onset of Char Method 318
10.6.4 Fire Test Performance 319
10.6.5 Timber Stud Walls 320
10.6.6 Calculation of Structural Performance 320
10.6.7 Buckling of Studs 322
10.6.8 End Restraint 323
10.6.9 Steam Softening 324
10.6.10 Finite Element Calculation Methods 324

10.7 Steel Stud Walls 325
10.7.1 Design of Steel Stud Walls 325

10.8 Timber Joist Floors 327
10.9 Timber Trusses 328

10.10 Construction Details 329
10.10.1 Number of Layers 329
10.10.2 Fixing of Sheets 329
10.10.3 Resilient Channels 331
10.10.4 Penetrations 332
10.10.5 Party Walls 333
10.10.6 Fire Stopping, Junctions 334
10.10.7 Conflicting Requirements 335
10.11 Lightweight Sandwich Panels
  10.11.1 Description 335
  10.11.2 Structural Behaviour 335
  10.11.3 Fire Behaviour 336
  10.11.4 Fire Resistance 337
  10.11.5 Design 339

11 Advanced Calculation Methods 340
  11.1 Types of Advanced Calculation Methods 340
  11.2 Fire Models 341
    11.2.1 Plume Models 342
    11.2.2 Zone Models 342
    11.2.3 CFD Models 343
    11.2.4 Post-flashover Fire Models 343
  11.3 Thermal Response Models 344
    11.3.1 Test Data and Simple Calculation Methods 344
    11.3.2 Thermal Modelling with Advanced Calculation Methods 344
  11.4 Advanced Structural Models 348
  11.5 Advanced Hand Calculation Methods 349
    11.5.1 Steel-concrete Composite Floors 349
    11.5.2 Tensile Membrane Action 349
    11.5.3 The Membrane Action Method 350
    11.5.4 The Slab Panel Method 353
    11.5.5 Failure Mechanisms of Composite Slabs 353
  11.6 Finite Element Methods for Advanced Structural Calculations 355
    11.6.1 Structural Behaviour Under Fire Conditions 355
    11.6.2 Finite Element Analysis Under Fire Conditions 358
    11.6.3 Material Properties 359
    11.6.4 Structural Properties 364
  11.7 Software Packages for Structural and Thermal Fire Analysis 369
    11.7.1 Generic Software Packages 369
    11.7.2 Specific Structural Fire Engineering Software 370

12 Design Recommendations 371
  12.1 Summary of Main Points 371
    12.1.1 Fire Exposure 371
    12.1.2 Fire Resistance 372
  12.2 Summary for Main Materials 372
    12.2.1 Structural Steel 372
    12.2.2 Reinforced Concrete 373
    12.2.3 Steel-concrete Composite Construction 374
    12.2.4 Heavy Timber 374
    12.2.5 Light Frame Construction 375
  12.3 Thermal Analysis 375
  12.4 Conclusions 376
Appendix A: Units and Conversion Factors
Appendix B: Section Factors for Steel Beams
References
Index