Modernization of Uzbekistan Building Code (UBC) System

Structural Fire Design for Buildings

Ahn, Jae-kwon

Korea Institute of Civil Engineering and Building Technology

국토교통부
Ministry of Land, Infrastructure and Transport

해외건설협회
International Contractors Association of Korea

KICT
한국건설기술연구원

서울시립대학교
UNIVERSITY OF SEOUL

RICON
KOREA RESEARCH INSTITUTE FOR CONSTRUCTION POLICY

Outline

- **Introduction to Fire Safety**
  - Background
  - Fire Safety
  - Fire Resistance
  - Current Issues

- **Fire and Heat**
  - Fuels & Fire Loads
  - Fire Behavior & Heat Transfer

- **Structural Fire Design in Codes and Standards**
  - Methods of Assessing Fire Resistance
  - Fire-resistance Requirements in Codes and Standards
  - Prescriptive Method & Calculation Method in IBC
  - Simple Calculation Method in EUROCODE

- **Advanced Structural Fire Design**
  - Background and Key Issues
  - Performance-based Design Process
  - Whole Building Behavior and the Use of Finite Element Models

Introduction to Fire Safety

- **Background**
  - Building fires cause the loss of life and damage to property.
  - Fire risk can be mitigated through conscientious design and maintenance.
    - Actually, it is impossible to prevent all major building fires.
  - Fire safety depends on numerous factors:
    - Fire prevention, suppression and extinction
    - Successful evacuation of occupants
    - **Structural integrity (or robustness)**

- **Fires**
  - The Great Fire of London
    - 2nd September 1666, London, UK
    - Within 5 days the city was destroyed by fire
    - 440 acres consumed, 87 churches, 13200 homes
  - World Trade Center
    - 11th September 2001, New York, USA
    - 2,763 people deaths in the WTC
    - Fire temperatures – about 1000° C
  - Grenfell Tower fire
    - 14th June 2017, London, UK
    - 72 people deaths & 70 people injured
    - Exterior cladding and insulation with combustible materials

Introduction to Fire Safety

- **Role of Structures**
  - Various occupancy
    - Building (commercial, industrial, residential), Outdoor stadium, Oil platform, Tower, Liquid storage tanks etc.
  - Provide comfortable, safe, functional space
    - Shelter and Support
    - Withstands various types of loads - Dead, Live, Wind, Flood, Snow, Earthquake, Thermal, and Fire

- **Fire Safety**
  - Not possible to prevent all fire scenarios
  - Designers need to put in-place strategies to minimize the occurrence of fires & consequently reducing their impact on life, property and environment.
  - Main strategies include providing for:
    - Automatic fire sprinklers - statistics show that sprinklers have a very high probability of controlling or extinguishing any fire
    - Systems for fire detection and notification of fire service
    - Safe travel paths for the movement of occupants & firefighters
    - Barriers to control the spread of fire & smoke
    - **Fire resistant structures - not collapse prematurely in fire**
  - To strategize, the designer has the important responsibility to properly select, design and use building materials

Introduction to Fire Safety

- **What is Fire Resistance?**
  - **Fire resistance**: “the property of a material or assemblage to withstand fire or give protection from it.
  - Provide physical barrier to restrict fire spread
    - prevent fire and smoke spread
    - safe evacuation of occupants & firefighter
    - minimize life loss and injury
  - Maintain structural integrity and load carrying ability against fire
    - Minimize property damage
    - prevent structural collapse
    - Compartmentation & Structural integrity are principal aspects of fire safety in buildings
    - Fire Resistance Rating – Codes
  - The importance of fire resistance depends on **the size of the building & the fire safety objectives** that need to be satisfied.

Introduction to Fire Safety

- **Issue 1 - Performance-based design codes**
  - Current approach to fire safety design: **Prescriptive based approach**
    - Significant drawbacks
  - Many countries including US and Europe are moving towards performance-based codes
    - Rational engineering approaches
    - Offers cost-effective, innovative & alternate designs
  - Performance-based design approach needs:
    - Validated models, test data for validation, material properties
    - Design tools/guidelines, trained personnel, monitoring tools

- **Issue 2 – New materials (High performance material)**
  - High Strength Concrete, Fiberglass Reinforced Plastic
    - Benefits: Superior performance(Strength, Durability, Corrosion resistance…)
    - Applications: Bridges, Infrastructure projects(Retrofitting & strengthening)
  - High Performance Material - Plastics, Composites
    - Benefits: Superior strength, Light weight
    - Applications: Auto, Aerospace, Transportation
  - Major problem in fire performance
    - High temperature intolerant
    - Toxicity
    - Flame spread (combustible)
    - Faster strength/stiffness degradation

Fire and Heat

Fuels – Materials

- Material available as fuel are part of the building structure, lining materials, or contents of the building
  - All materials are hydrocarbons, their molecules consisting mainly of carbon & atoms, with the addition of oxygen, nitrogen & others in some cases

Fuels – Calorific Value

- **Heat release rates (HRR)** from combustion depend on the nature of the burning material, the size of the fire, and the amount of air available.
- The calorific value or heat of combustion is the amount of heat released during complete combustion of a unit mass of fuel.
  - Most solid, liquid and gaseous fuels have a calorific value between 15 and 50 MJ/kg
  - Net calorific values of combustible materials for calculation of fire loads in EUROCODE 1

Combustible materials		MJ/kg
Solid	Wood	17.5
	Clothes, Cork, Cotton, Paper, cardboard, Silk, Straw, Wool	20
	Carbon: Anthracit, Charcoal, Coal	30
Chemicals	Methane, Ethane, Propane, Butane	50
	Ethylene, Propylen, Butene	45
	Benzene, Toluene	40
	Methanol, Ethanol, Ethyl alcohol	30
	Gasoline, petroleum Diesel, Pure hydrocarbons	45
	Polyethylene, Polystyrene, Polypropylene	40

Fire and Heat

Fire Load

- Fire load in buildings is usually expressed as **Fire Load Energy Density per floor area(MJ/m²).**
  - Note that some references express fire load as energy density per total room bounding surfaces.

Design Fire Load

- should be determined in a similar way to design loads
  - Earthquake load vs. Extreme likely design fire scenario
- should reflect almost the maximum fire load expected in building life
- Both fixed and moveable fire loads should be included.
- Fire load densities qf,k [MJ/m²] for different occupancies in EUROCODE 1

Occupancy	Average (MJ/kg)	80% Fractile (MJ/kg)
Dwelling	780	948
Hospital	230	280
Hotel	310	377
Library	1500	1824
Office	420	511
Classroom of a school	285	347
Shopping centre	600	730
Theatre (cinema)	300	365
Transport (public space)	100	122

Fire and Heat

Heat Release Rate & t-squared Fires

Heat release rate (HRR)

- The HRR (MW) can be calculated by the amount of heat (MJ) released in a certain time (s).

$$Q = E/t$$

1) E is the total energy contained in the fuel (MJ)
2) t is the duration of the burning (s)

t-squared fires

- characterized by a parabolic curve with the HRR proportional to the time squared

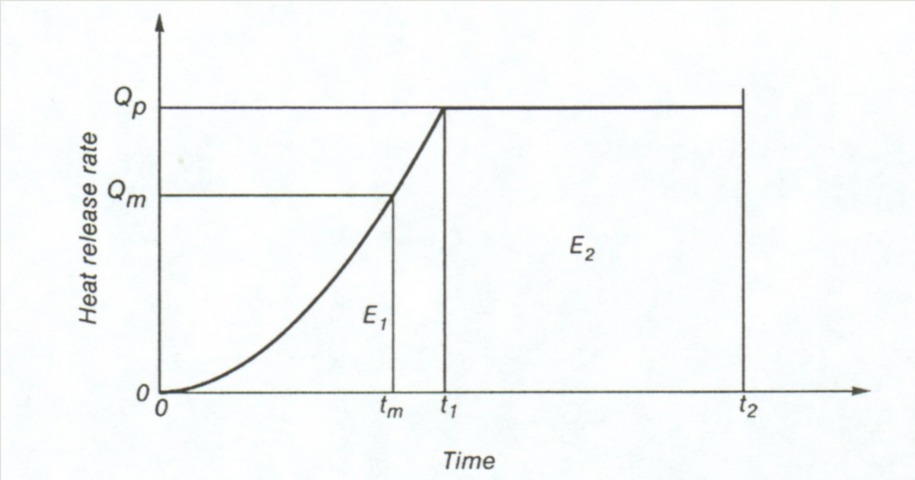
$$Q = (t/k)^2 = (\alpha\, t)^2$$

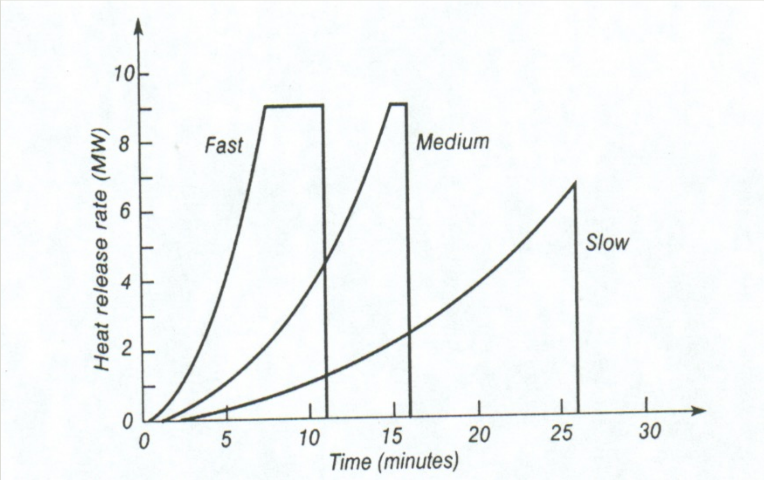
1) Q is the HRR (MW), t is the time (s),
2) k is the growth constant (s/MW$^{1/2}$), and α is the fire intensity coefficient (MW/s^2)

Fire Growth Rate	Growth Constant	Fire Intensity Coefficient	Typical Real Fire
Slow	600	0.00293	Densely packed wood products
Medium	300	0.0117	Solid wood furniture such as desk Individual furniture items with small amount of plastic
Fast	150	0.0466	Some upholstered furniture High stacked wood pallets Cartons on pallets
Ultra-fast	75	0.1874	Most upholstered furniture High stacked plastic materials Thin wood furniture such as wardrobs

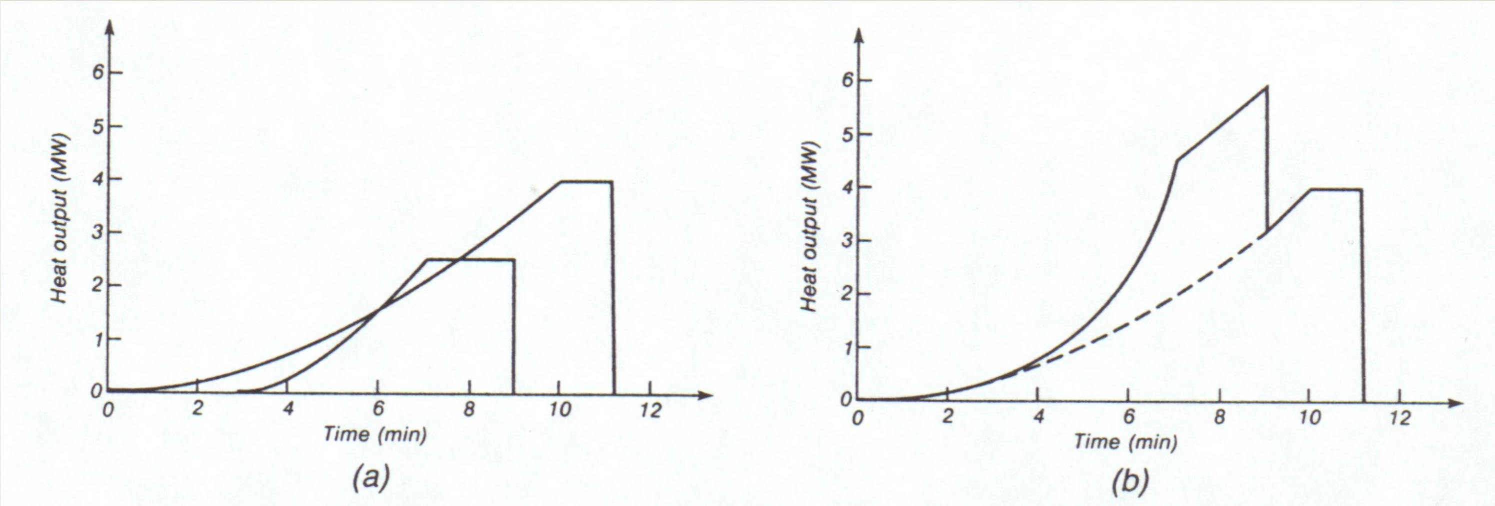
Fire and Heat

- **Heat Release Rate & t-squared Fires**
  - Variation of HRR (same fire load): **slow, medium and fast fire growth rates**





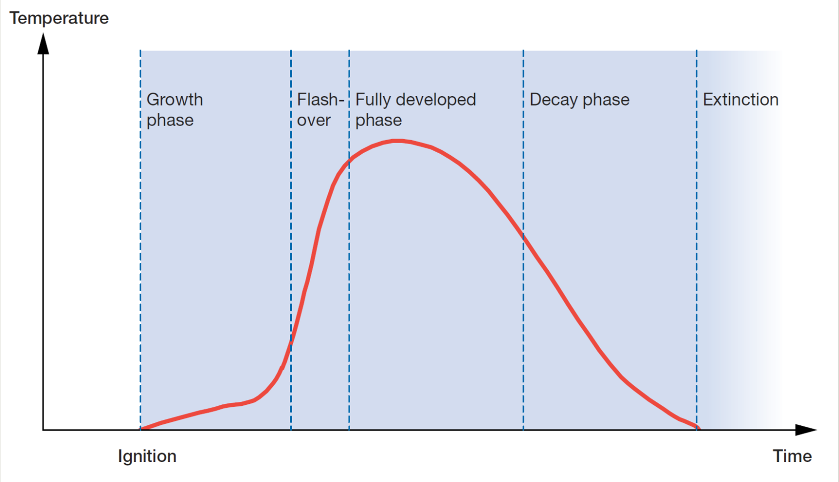
  - Combination of t-squared HRRs for separately & combined for two objects



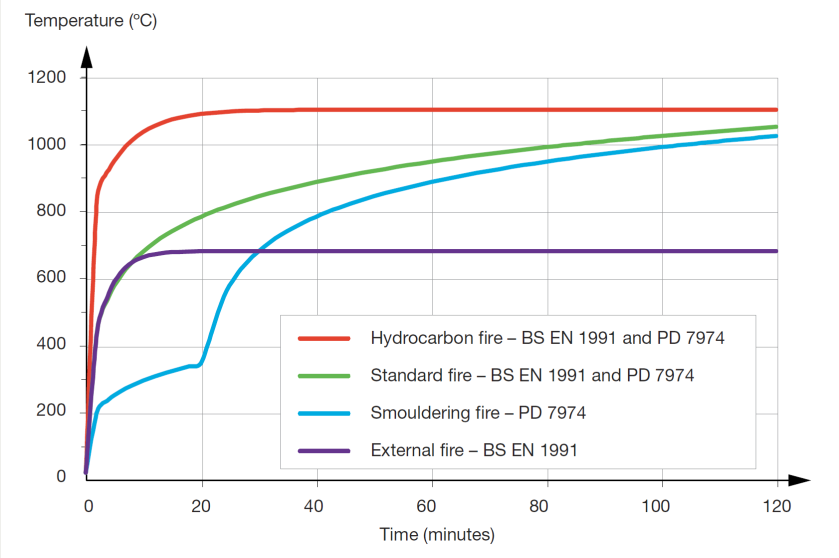
Fire and Heat

▪ Fire Behavior in Building Compartment

- **The factors influencing the severity of a fire** in a compartment are:
  - fire load type, density and distribution
  - combustion behavior of the fire load
  - compartment size and geometry
  - ventilation conditions of the compartment
  - thermal properties of the compartment boundary



- **Stages of an enclosed compartment fire**
  - Growth phase(pre-flashover)
  - Flashover
  - Fully developed phase (post-flashover)
  - Decay phase
  - Extinction



- Options for **modelling compartment fires**
  - Nominal fire
  - Time equivalence
  - Natural fire curves
  - Localized fires
  - Zone models
  - CFD/field models

Fire and Heat

Heat Transfer - Conduction

- Conduction is the mechanism for heat transfer in solid materials
  - factor in the ignition of solid surfaces, & in the fire resistance of barriers & structural members
  - Thermal properties needed for heat transfer calculations in solid materials include:
    1) density, ρ (kg/m^3), specific heat, C_p (J/kg-K), thermal conductivity, k (W/m-K)
    2) thermal diffusivity, $\alpha = k/\rho C_p$ (m^2/s), thermal inertia, $k\rho C_p$ (W^{2}s/m^{4}K^2)

Heat Transfer - Convection

- Convection is heat transfer by the movement of fluids, either gases or liquids
  - Heat transfer by convection is an important factor in flame spread and in upward transport of smoke and hot gases to the ceiling or out of the window from a room fire
  - Convective heat transfer is usually taken to be directly proportional to the temp difference between 2 materials

Fire condition	convection coefficient (W/m^{2}K)
Standard fires	25
External fires	25
Hydrocarbon fires	50
Parametric fires	35
Unexposed side (without & with radiation)	4 & 9

Heat Transfer - Radiation

- Radiation is the transfer of energy by waves
- **Very important in fires because it is the main mechanism for heat transfer** from:
  - flames to fuel surfaces
  - hot smoke to building objects
  - a burning building to an adjacent building

Material	Emissivity
Carbon steel	0.7
Stainless steel	0.4
Concrete	0.7
Others	0.8

Structural Fire Design in Codes and Standards

Methods of Assessing Fire Resistance

- The fundamental step in designing structures for fire safety is to verify that **the fire resistance of the structure is greater than the severity of the fire to which the structure is exposed**.

Fire resistance ≥ Fire severity

  - Fire resistance is a measure of the ability of the structure to resist collapse or fire spread during exposure to a fire of specified severity.
  - Fire severity is a measure of the destructive impact of a fire, or the forces or temp. that may cause collapse or fire spread as a result of a fire.

- Methods for comparing fire severity with fire resistance
  - The most common verification is comparing fire severity and fire resistance in time domain.
  - Temperature domain is more suitable for barriers than structural elements.
  - Load capacity in a fire can be calculated using thermal & structural analyses at high temperature.
  - Prescriptive codes specify required fire resistance which is generally between half an hour and four hours, but with no reference to the severity of the expected fire
  - Performance-based codes allow the use of time equivalent formulae to improve on simple prescriptive fire-resistance requirements

Domain	Fire Resistance	Fire severity
Time	Time to failure	Fire duration as calculated or specified by codes
Temperature	Temperature to cause failure	Maximum temperature reached during the fire
Strength	Load capacity at elevated temperature	Applied load during the fire

Structural Fire Design in Codes and Standards

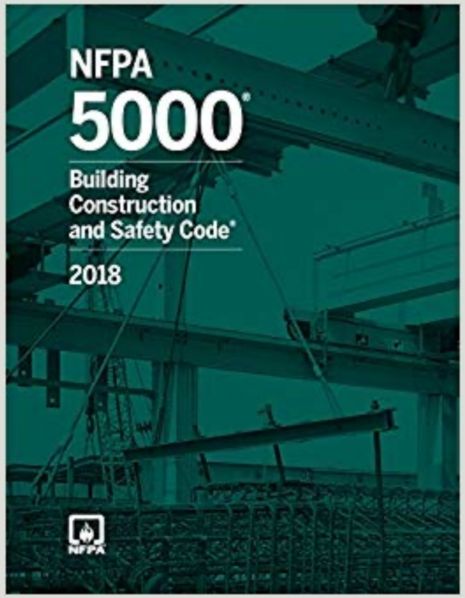
Fire-resistance Requirements in Codes and Standards

- Building codes set fire-resistance requirements for building assemblies to resist
  - Spread of fire within buildings
  - Collapse of structural elements exposed to fire

- **Construction type & Occupancy**

  - **Construction type**
    1) Type I & II - Non-combustible : Concrete, Masonry, Steel
    2) Type III - Non-combustible exterior walls & Combustible/Non-combustible interior elements
    3) Type IV - Non-combustible exterior walls & Interior elements of solid wood, laminated wood, heavy timber (HT)
    4) Type V - allows the use of all types of materials, both noncombustible and combustible.

  - **Occupancy**
    1) Assembly
    2) Business
    3) Educational
    4) Factory & Industrial
    5) High Hazard
    6) Institutional
    7) Mercantile
    8) Residential
    9) Storage
    10) Utility/Miscellaneous



Structural Fire Design in Codes and Standards

▪ Fire-resistance Requirements in Codes and Standards

- **Maximum allowable height & area of a building** are determined based on
  - Construction type & Occupancy

TABLE 504.3
ALLOWABLE BUILDING HEIGHT IN FEET ABOVE GRADE PLANE[a]

OCCUPANCY CLASSIFICATION	SEE FOOTNOTES	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
		A	B	A	B	A	B	HT	A	B
A, B, E, F, M, S, U	NS[b]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85	75	85	75	85	70	60
H-1, H-2, H-3, H-5	NS[c, d] / S	UL	160	65	55	65	55	65	50	40
H-4	NS[c, d]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85	75	85	75	85	70	60
I-1 Condition 1, I-3	NS[d, e]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85	75	85	75	85	70	60
I-1 Condition 2, I-2	NS[d, e, f]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85						
I-4	NS[d, g]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85	75	85	75	85	70	60
R[h]	NS[d]	UL	160	65	55	65	55	65	50	40
	S13D	60	60	60	60	60	60	60	50	40
	S13R	60	60	60	60	60	60	60	60	60
	S	UL	180	85	75	85	75	85	70	60

Structural Fire Design in Codes and Standards

Fire-resistance Requirements in Codes and Standards

- **Fire-resistance rating requirements** for building elements in IBC (hours)

Building element	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE IV	
	A	B	A	B	A	B	HT	A	B
Primary structural frame	3	2	1	0	1	0	HT	1	0
Exterior bearing walls	3	2	1	0	2	2	2	1	0
Interior bearing walls	3	2	1	0	1	0	1/HT	1	0
Floor	2	2	1	0	1	0	HT	1	0
Roof	1½	1	1	0	1	0	HT	1	0

- **Construction types** in NFPA 220 (Standard on types of building construction)
  - 3 Digit Code: e.g. 332.
  - 1st digit: fire resistance of exterior bearing wall
  - 2nd digit: fire resistance of columns, beams, girders, trusses and arches
  - 3rd digit: fire resistance of floor construction

IBC/IFC:	UBC/UFC:	NFPA:	NFIRS:	BOCA:	SBC:	COMMON TERMINOLOGY:
-----	-----	I (443)	1	1-A	I	Fire Resistive, Non-combustible
Type I-A	Type I-FR	I (332)	1	1-B	II	Fire Resistive, Non-combustible
Type I-B	Type II-FR	II (222)	1	2-A	-----	Fire Resistive, Non-combustible
Type II-A	Type II-1 Hr.	II (111)	3	2-B	IV-1 Hr.	Protected Non-combustible
Type II-B	Type II-N	II (000)	4	2-C	IV-unp.	Unprotected Non-combustible
Type III-A	Type III-1 Hr	III (211)	5	3-A	V-1 Hr.	Protected Ordinary
Type III-B	Type III-N	III (200)	6	3-B	V-unp.	Unprotected Ordinary
Type IV	Type IV (H.T.)	IV (2HH)	2	4	III	Heavy Timber
Type V-A	Type V-1 Hr	V (111)	7	5-A	VI-1 Hr.	Protected Combustible
Type V-B	Type V-N	V (000)	8	5-B	VI-unp.	Unprotected Combustible

Structural Fire Design in Codes and Standards

▪ Traditional Approaches to Structural Fire Design

• Standard fire test

- Most countries assess fire performance of building materials & elements using full-size fire resistance tests
- Refer to results from standard test; no “engineering analysis” required
- More than 100 years
- ASTM E119, NFPA 251, UL 263, ISO 834, BS 476

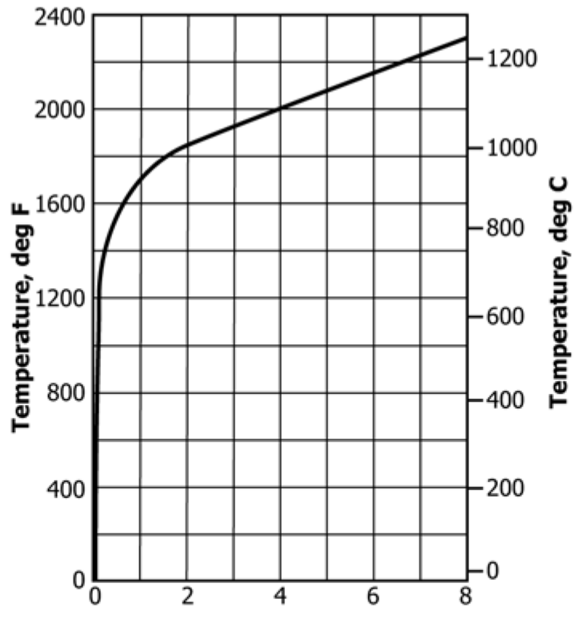
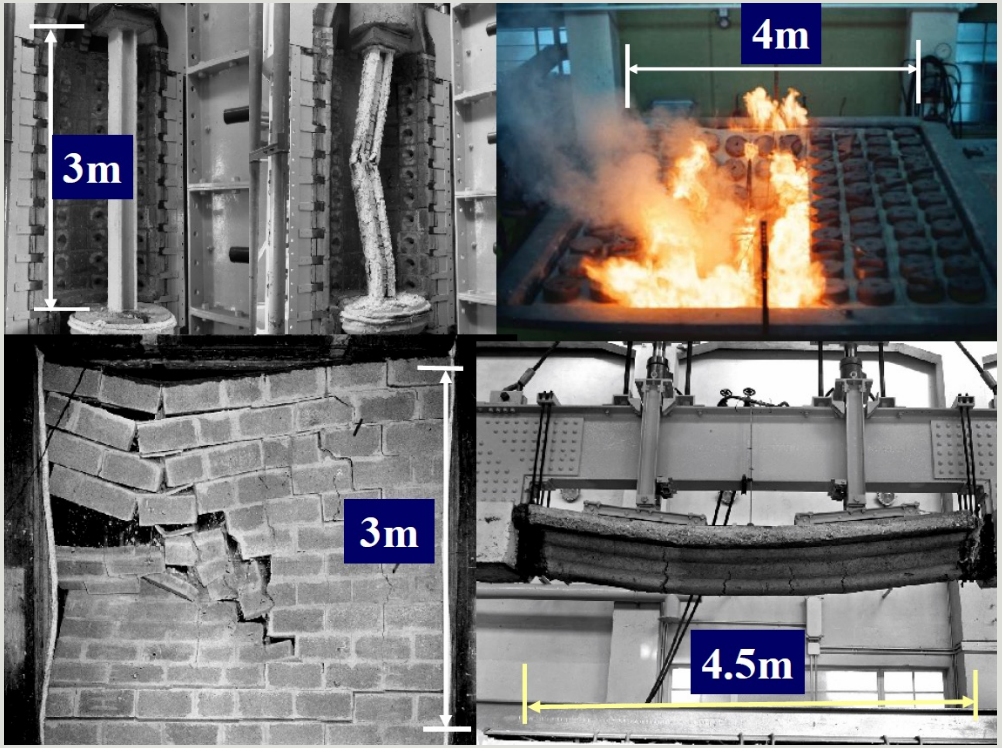


FIG. 1 Time-Temperature Curve



Structural Fire Design in Codes and Standards

▪ Traditional Approaches to Structural Fire Design

- **Code-based prescriptive design**
  - Most codes have been prescriptive in nature for fire resistance evaluation.
  - Code-based prescriptive design may restrict designers to take a rational engineering approach to the provisions of fire safety

- **Minimum protection of structural parts based on time periods for various noncombustible insulating materials**

Structural parts	Insulating material	Minimum thickness for required fire resistance time (inches)			
		4 hours	3 hours	2 hours	1 hour
Steel columns and all of primary trusses	Carbonate, lightweight and sand-lightweight aggregate concrete, members 6”×6” or greater	2.5	2	1.5	1
	Carbonate, lightweight and sand-lightweight aggregate concrete, members 8”×8” or greater	2	1.5	1	1
	Carbonate, lightweight and sand-lightweight aggregate concrete, members 12”×12” or greater	1.5	1	1	1
	Siliceous aggregate concrete, members 6”×6” or greater	3	2	1.5	1
	Siliceous aggregate concrete, members 8”×8” or greater	2.5	2	1	1
	Siliceous aggregate concrete, members 12”×12” or greater	2	1	1	1
Webs or flanges of steel beams and girders	Carbonate, lightweight and sand-lightweight aggregate concrete with 3” or finer metal mesh placed 1” from the finished surface anchored to the top flange and providing no less than 0.025 square inch of steel area per foot in each direction	2	1.5	1	1
	Siliceous aggregate concrete and concrete excluded in Item 2-1.1 with 3" or finer metal mesh placed 1" from the finished surface anchored to the top flange and providing not less than 0.025 square inch of steel area per foot in each direction.	2.5	2	1.5	1

Structural Fire Design in Codes and Standards

IBC - Calculation Method for Fire Resistance of Structures

- includes **the methods to calculate the fire-resistance rating** for an assembly (concrete, concrete-masonry, clay masonry, steel and wood).

TABLE 722.2.3(1)
COVER THICKNESS FOR REINFORCED CONCRETE FLOOR OR ROOF SLABS (inches)

CONCRETE AGGREGATE TYPE	FIRE-RESISTANCE RATING (hours)									
	Restrained					Unrestrained				
	1	$1^1/_2$	2	3	4	1	$1^1/_2$	2	3	4
Siliceous	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	1	$1^1/_4$	$1^5/_8$
Carbonate	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$1^1/_4$	$1^1/_4$
Sand-lightweight or lightweight	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$1^1/_4$	$1^1/_4$

For SI: 1 inch = 25.4 mm.

TABLE 722.2.3(2)
COVER THICKNESS FOR PRESTRESSED CONCRETE FLOOR OR ROOF SLABS (inches)

CONCRETE AGGREGATE TYPE	FIRE-RESISTANCE RATING (hours)									
	Restrained					Unrestrained				
	1	$1^1/_2$	2	3	4	1	$1^1/_2$	2	3	4
Siliceous	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$1^1/_8$	$1^1/_2$	$1^3/_4$	$2^3/_8$	$2^3/_4$
Carbonate	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	1	$1^3/_8$	$1^5/_8$	$2^1/_8$	$2^1/_4$
Sand-lightweight or lightweight	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	$^3/_4$	1	$1^3/_8$	$1^1/_2$	2	$2^1/_4$

For SI: 1 inch = 25.4 mm.

Structural Fire Design in Codes and Standards

IBC - Calculation Method for Fire Resistance of Structures

- also contains provisions that would permit modifications or changes to a tested assembly.

TABLE 722.2.2.1
MINIMUM SLAB THICKNESS (inches)

CONCRETE TYPE	FIRE-RESISTANCE RATING (hours)				
	1	$1^1/_2$	2	3	4
Siliceous	3.5	4.3	5	6.2	7
Carbonate	3.2	4	4.6	5.7	6.6
Sand-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

For SI: 1 inch = 25.4 mm.

TABLE 722.2.4
MINIMUM DIMENSION OF CONCRETE COLUMNS (inches)

TYPES OF CONCRETE	FIRE-RESISTANCE RATING (hours)				
	1	$1^1/_2$	2[a]	3[a]	4[b]
Siliceous	8	9	10	12	14
Carbonate	8	9	10	11	12
Sand-lightweight	8	$8^1/_2$	9	$10^1/_2$	12

For SI: 1 inch = 25 mm.

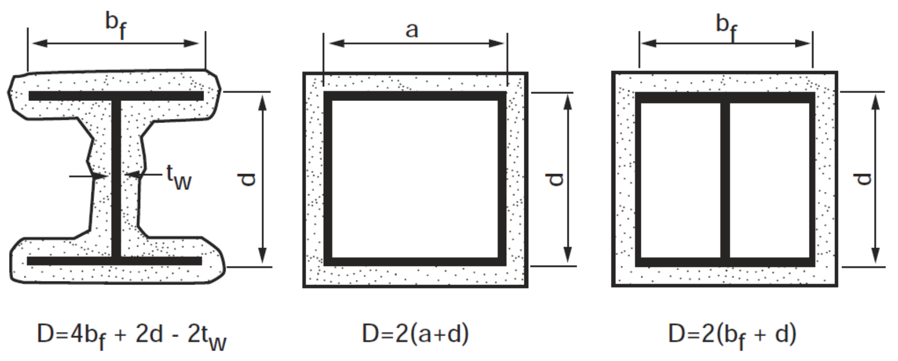


FIGURE 722.5.1(1)
DETERMINATION OF THE HEATED PERIMETER OF STRUCTURAL STEEL COLUMNS

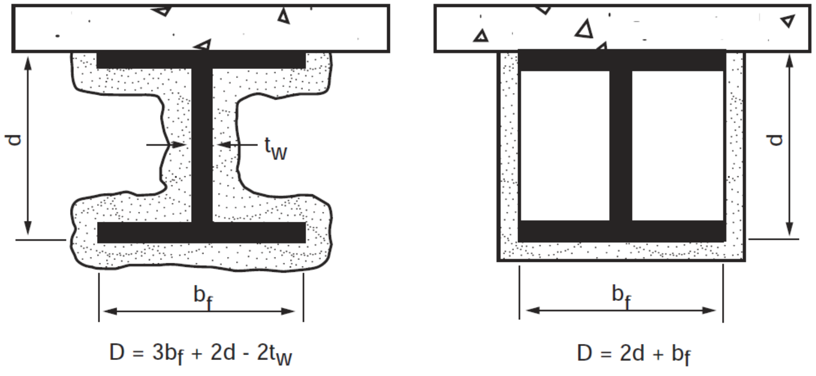


FIGURE 722.5.2
DETERMINATION OF THE HEATED PERIMETER OF STRUCTURAL STEEL BEAMS AND GIRDERS

Structural Fire Design in Codes and Standards

Structural Design in Fire Conditions

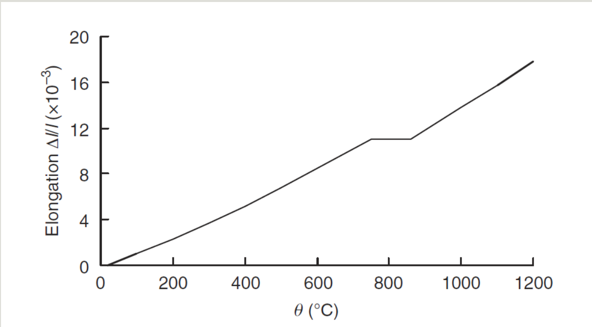
- In concept, structural design for fire exposed to fire
  - similar to structural design for room temperature conditions
  - must establish clear objectives & determine design fire severity
  - Working stress or ultimate strength design may be carried out

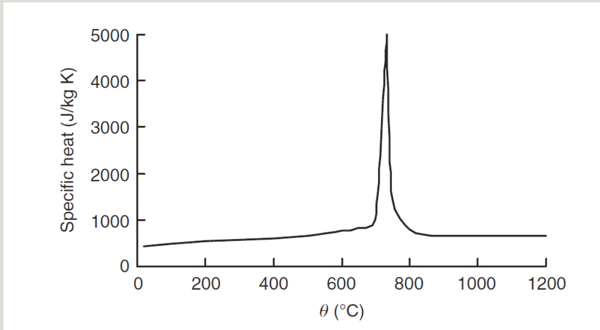
- Main differences between fire & ambient design are:
  - applied loads are less
  - internal forces may be induced by thermal expansion
  - strength of materials may be reduced by elevated temp.
  - cross-sectional areas may be reduced, i.e., charring
  - smaller safety factors used
  - deflections with no effect on strength are not important
  - different failure mechanisms need to be considered

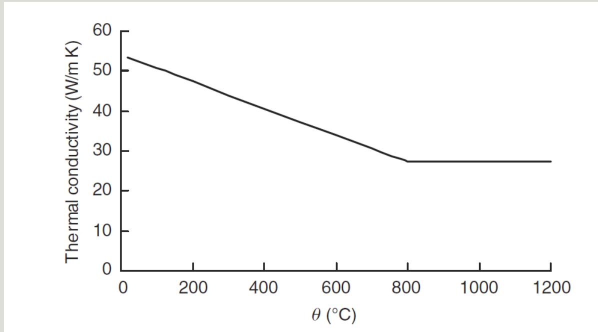
- Tools available to predict structural fire resistance of a load-bearing members include:
  - Hand calculations
  - Design charts
  - Computer programs

Structural Fire Design in Codes and Standards

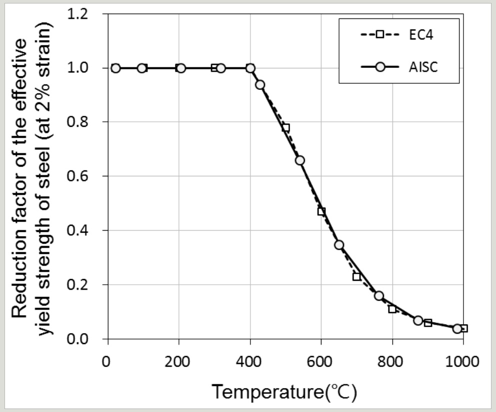
- **Thermal and mechanical properties of materials**
  - Thermal properties
    - Thermal elongation
    - Specific heat
    - Thermal conductivity
    - Density

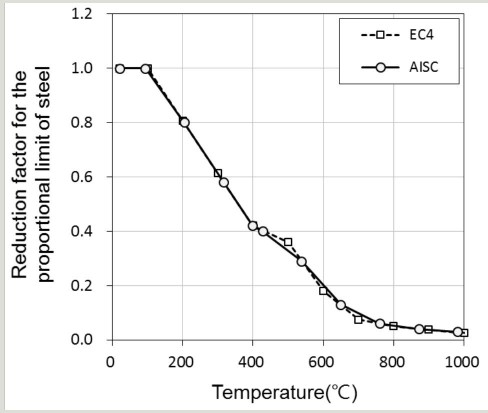


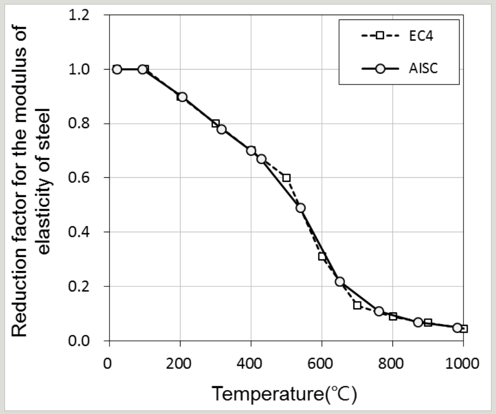


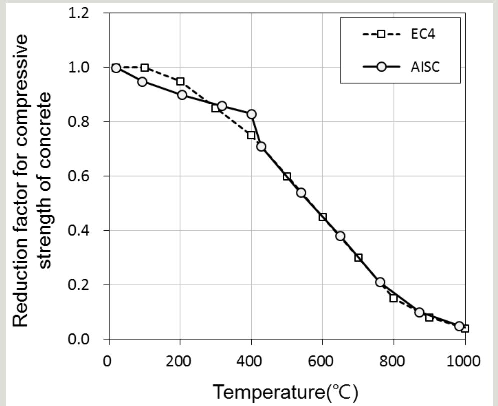


  - Mechanical properties
    - Stress-strain relationship: Effective yield strength, Slope of the linear elastic range, Proportional limit





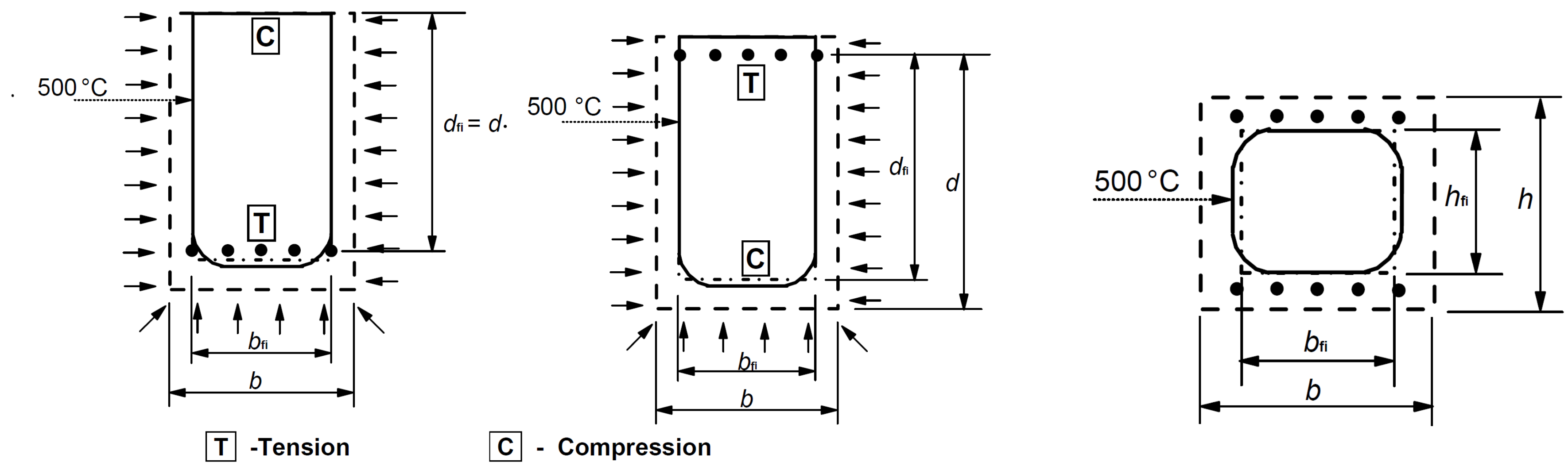




Structural Fire Design in Codes and Standards

Simple calculation method in EUROCODE

- Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design
  - **Two simplified methods using a reduced cross-section**
  - **applicable to structures subjected to a standard fire exposure**
  - **500°C isothermal method**
    1) concrete at a temperature more than 500°C is neglected in the calculation of load-bearing capacity
    2) concrete at a temperature below 500 °C is assumed to retain its full strength.
  - **Zone method**
    1) the fire damaged cross-section is reduced by ignoring a damaged zone at the fire-exposed surfaces.



a) fire exposure on three sides with the tension zone exposed

b) fire exposure on three sides with the compression zone exposed

c) fire exposure on four sides (beam or column)

Structural Fire Design in Codes and Standards

- **Simple calculation method in EUROCODE**
  - Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design
    - Simplified methods modifying the design resistance for normal temperature design
    - usually used the hypothesis of a uniform temperature in the cross-section
  - Eurocode 4: Design of composite steel and concrete structures - Part 1-2: General rules - Structural fire design
    - Simplified methods considering composite effects of steel and concrete
    - Detailed procedure of simple calculation for composite column

Plastic resistance to axial compression under fire ($N_{fi,\,pl}$)

↓

Effective flexural stiffness ($EI_{fi,\,eff}$) & Euler buckling load ($N_{fi,\,cr}$)

↓

Relative slenderness (λ_T)

↓

Reduction coefficient (χ) for buckling curve

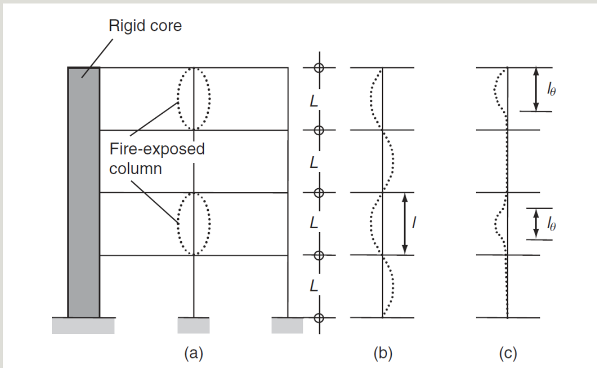
↓

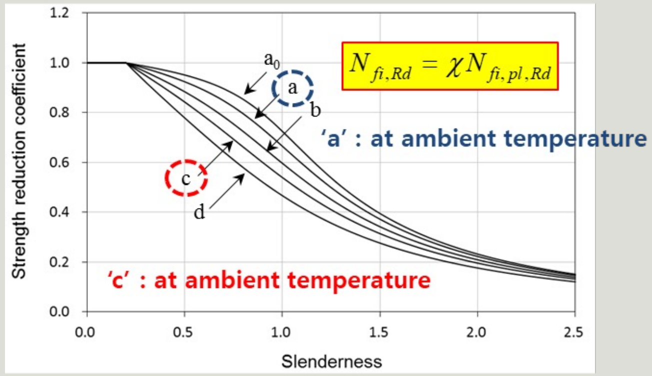
Evaluation of axial compressive resistance under fire (N_{fi})

$$N_{fi,pl,Rd} = \sum_j \left(A_{s,T} f_{s,T}\right) / \gamma_{M,fi,s} + \sum_k \left(A_{sr,T} f_{sr,T}\right) / \gamma_{M,fi,sr} + \sum_m \left(A_{c,T} f_{c,T}\right) / \gamma_{M,fi,c}$$

$$(EI)_{fi,eff} = \sum_j \left(\varphi_{s,T} E_{s,T} I_{s,T}\right) + \sum_k \left(\varphi_{sr,T} E_{sr,T} I_{sr,T}\right) + \sum_m \left(\varphi_{c,T} E_{sec,T} I_{c,T}\right)$$

$$\bar{\lambda}_T = \sqrt{N_{fi,pl,Rd} / N_{fi,cr}} \quad \left(N_{fi,cr} = \pi^2 (EI)_{fi,eff} / l_T^{\,2}\right)$$





Advanced Structural Fire Design

▪ Performance-based design

- **Disadvantages** of prescriptive approach
  - Actual structural behavior & Real fire effect are ignored.
  - Levels-of-safety and robustness are unknown.
  - Optimum solution for life safety, economical impact and environmental damage are unknown.

- Many countries are moving towards performance-based codes which
  - Sate how a building is to perform under a wide range of conditions
  - Use of calculation/engineering methods
  - Allow actual behavior and robustness of the building to be assessed
  - Allow designers to use alternate fire safety strategies, provided adequate safety can be demonstrated
  - Allow optimum design solution taking into account life safety, financial impact and environmental issues
  - can be used to justify cost-effective solutions
  - Can be used as part of an assessment of multiple risks

- Within a prescriptive code, there may be possibility to allow for performance-based selection of structural assemblies
  - if a code specifies a floor with a fire resistance rating, designers have the flexibility to select from a range of listed systems which have sufficient fire resistance

- However, Standard calculation methods have not yet been developed for widespread use

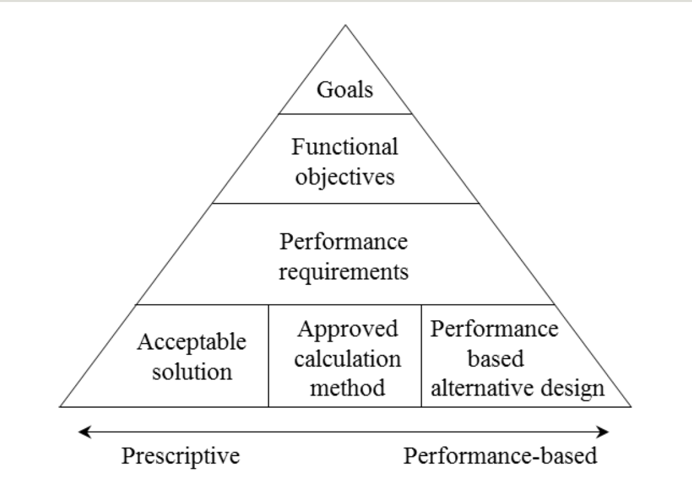
Advanced Structural Fire Design

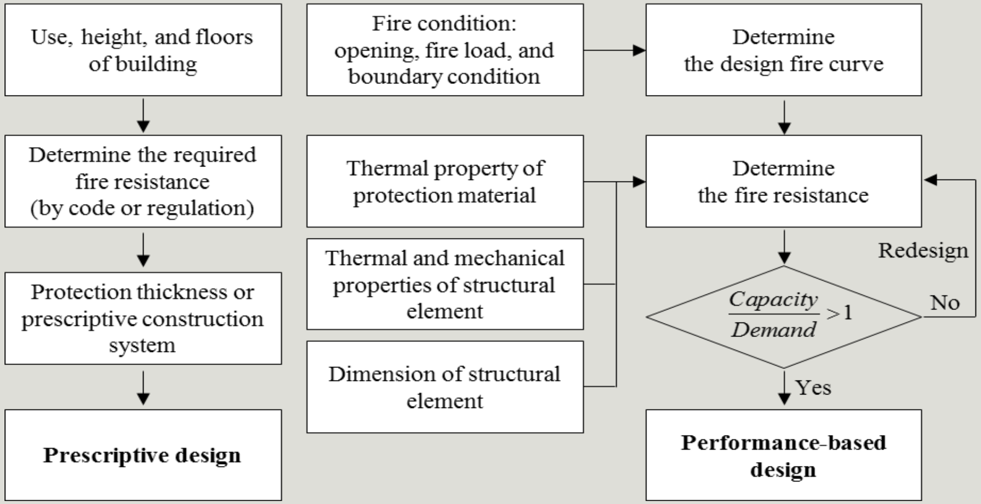
▪ Performance-based design

- In developing new codes, many countries have adopted a multi-level code format in the form of:
  - overall goals, functional objectives and required performance which must be achieved
  - selection of alternative means of achieving those goals. The three most common options are:
    1) to comply with a prescriptive 'Acceptable Solution'
    2) to comply with an approved standard calculation method
    3) to perform a performance-based fire engineering design from first principles

- So, compliance with performance-based codes is usually achieved by:
  - Mainly satisfying the requirements of acceptable solutions, or
  - Carrying out a performance-based alternative design based on fire engineering principles

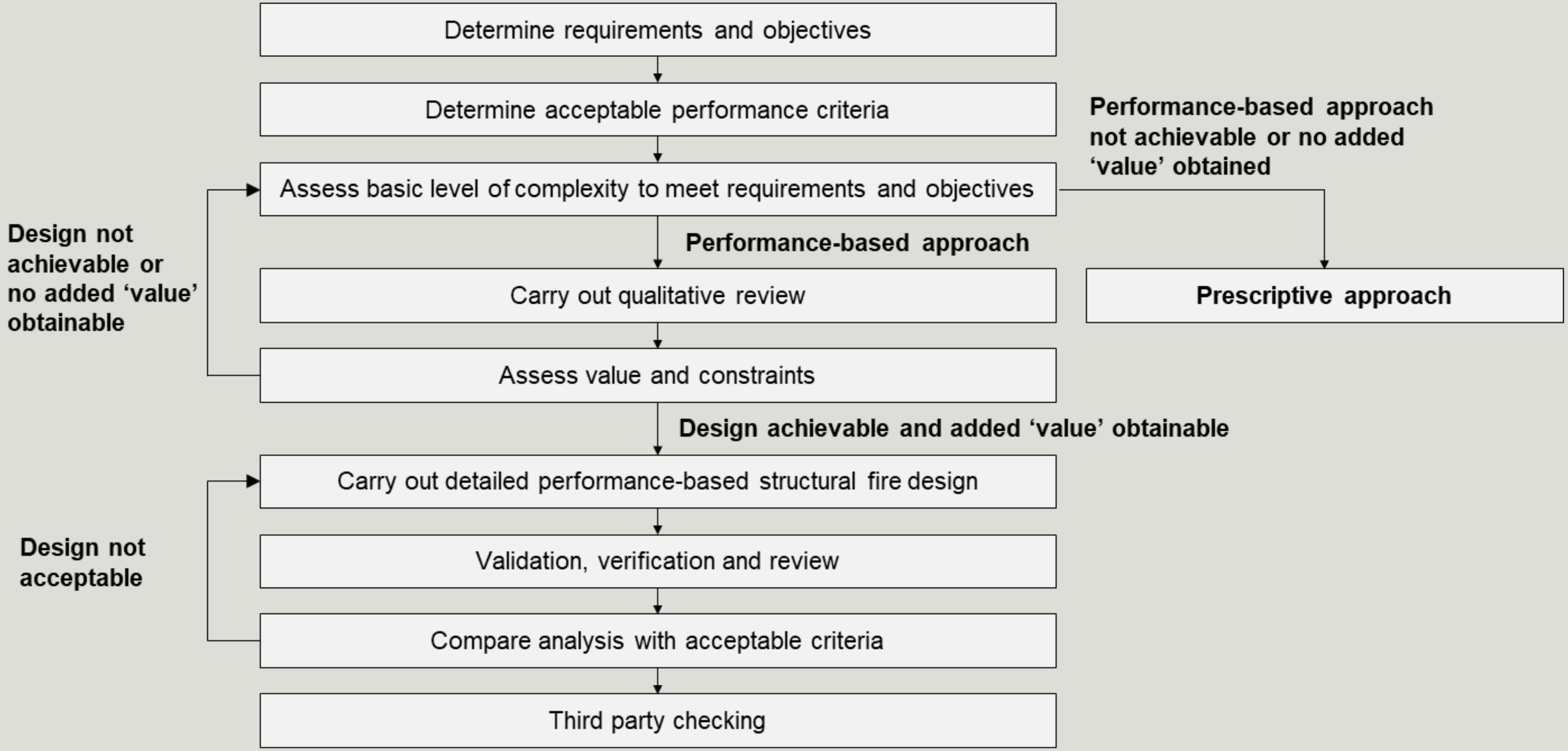
- Under a performance-based design, it is essential to have comprehensive documentation & quality control
  - The calculations should be included in a report which describes the building & the complete fire design process



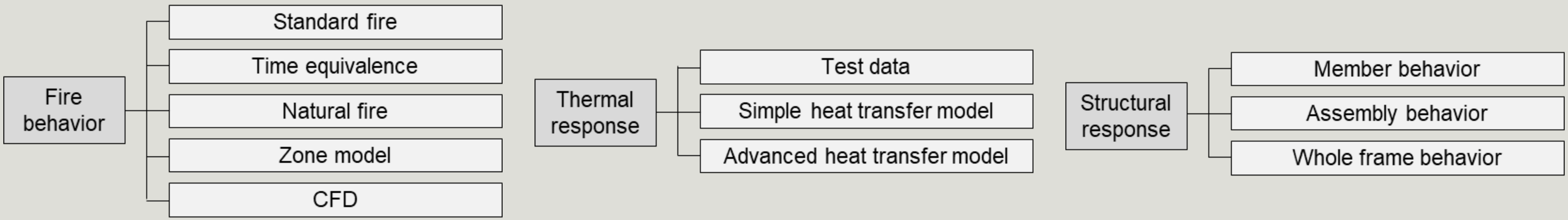


Advanced Structural Fire Design

- **Performance-based design process**



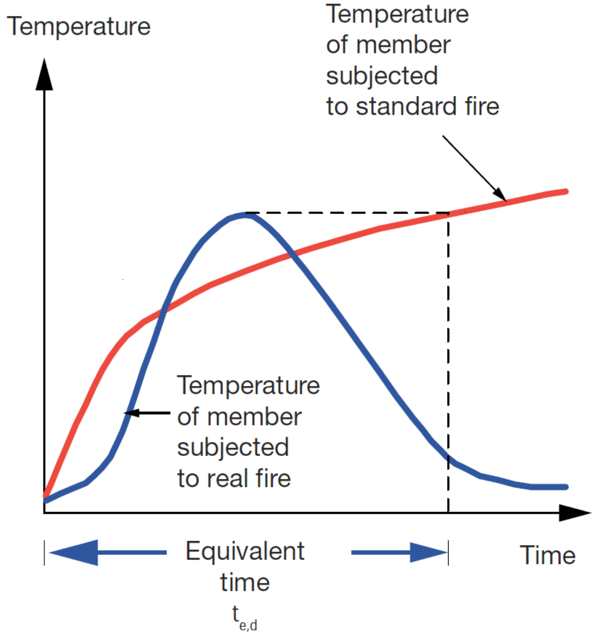
- **Three components of structural fire engineering design**

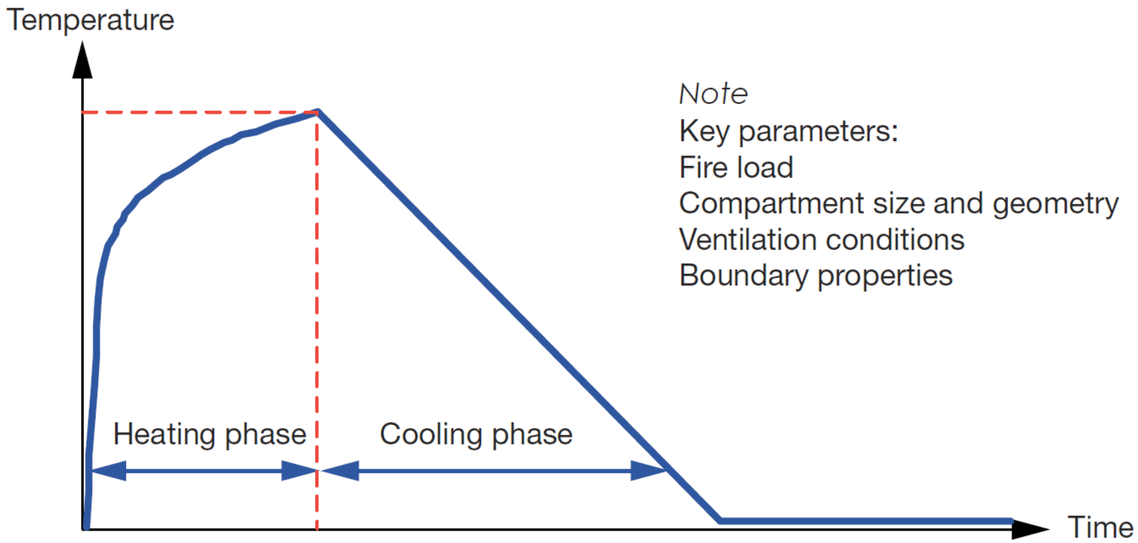


Advanced Structural Fire Design

▪ Assessment methods for thermal exposure

Assessment Method	Model for thermal Exposure	Description
Level 1	H1	**Standard fire exposure** – test or tabulated data
Level 2	H2	**Equivalent fire duration time** – relates the severity of a compartment fire to an equivalent period in a standard furnace
Level 3	H3	**Parametric exposure** – uses physical characteristics of the fire compartment as input parameters
Level 4	H4	**Advanced methods** – zone or field models used to characterize the full compartment response for the required duration





Note
Key parameters:
Fire load
Compartment size and geometry
Ventilation conditions
Boundary properties

Advanced Structural Fire Design

- **Options for estimating the heat transfer**

Model	Design charts/test data	Simple formulae	Advanced models
Complexity	Simple	Intermediate	Advanced
Analysis ability	• Exact solution • Standard fire condition	• Empirical solution • Standard fire condition	• Accurate solution • Any fire condition
Member types	• Dependent on available test data	• Mainly steel members	• Any material and construction methods
Input parameters	• Construction type & • Member geometry	• Heat flux or fire curves, Boundary conditions, • Member geometry, Material thermal properties	
Solutions	• Cross-sectional temperature charts • Tabulated thermal data	• Simple cross-sectional temperature profile	• One to three-dimensional time and space dependent temperature profile
Design tools	• Fire part of Eurocodes • Test/Research reports	• Fire part of Eurocodes • Design guides	• Finite element package
	Design charts/tables	Spreadsheet	Computer models

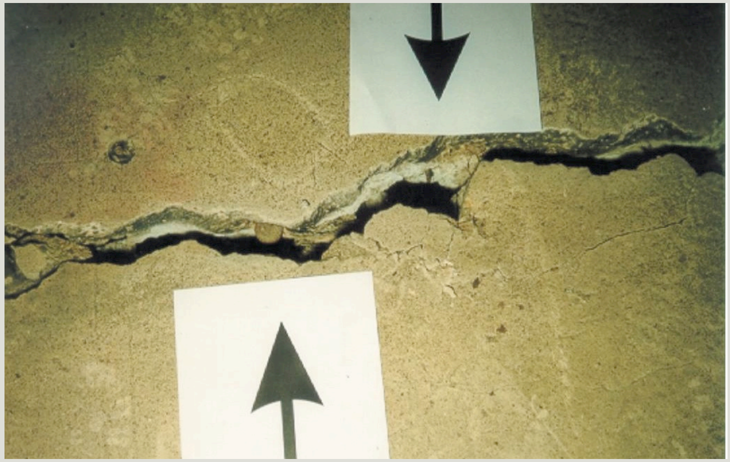
Advanced Structural Fire Design

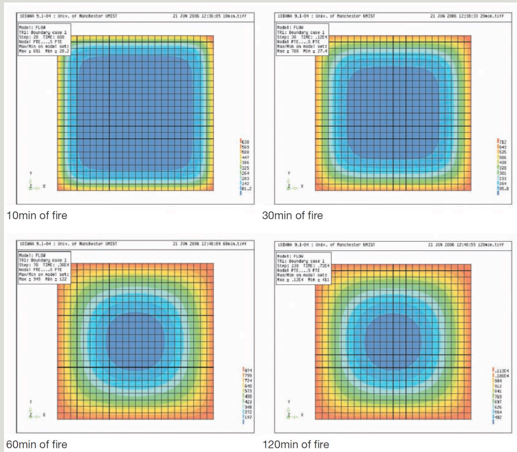
Options for Structural Analysis

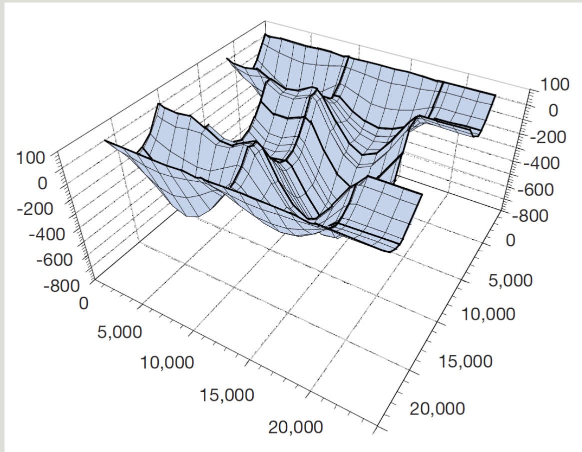
Model	Design charts/test data	Simple formulae	Advanced models
Complexity	Simple	Intermediate	Advanced
Input parameters	• Temperature through the cross-section • Material strength and stiffness reduction • Applied static load • Simplified boundary conditions	• Temperature through the cross-section and along the member • Material strength and stiffness reduction • Applied static load • Boundary conditions	• Temperature through and along the cross- section • Full material stress-strain-temperature relationship • Applied static load • Boundary conditions • Element type and density
accuracy	• Ignores real behaviour but assumed to be conservative • Ultimate strength calculation	• Begins to consider actual load paths and restraint • Ultimate strength calculation	• Predicts internal stresses, displacements, and rotations for all members throughout the duration of the fire • Localized behavior is not modelled accurately in whole building modelling
design tools	• Simple equations for hand calculations	• Simple equations for hand calculations • Plastic design, redistribution of moments • Simple computer models	• Commercially available or purpose written computer software

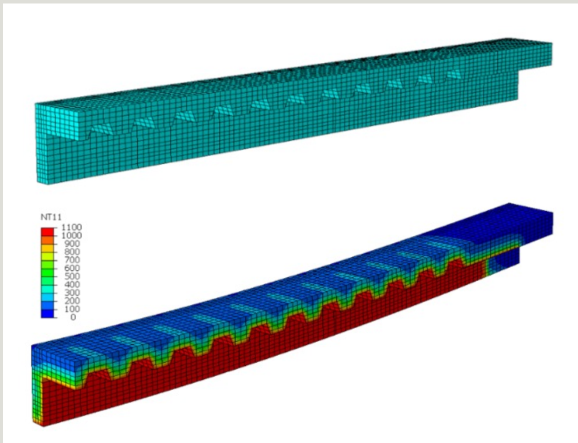
Advanced Structural Fire Design

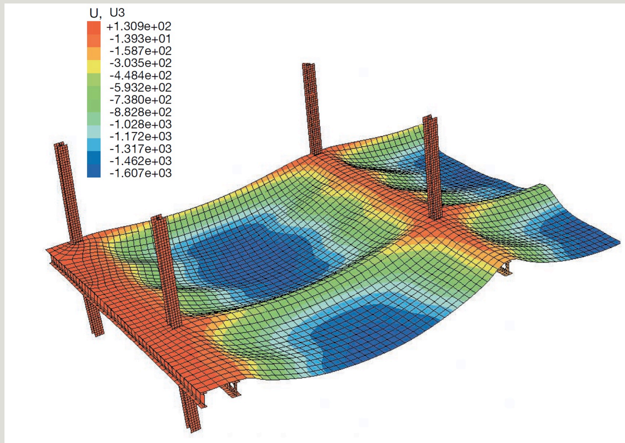
- **Whole building behavior and the use of advanced models**
  - Purpose-written or commercially available finite element software can be used to assess the structural response under fire conditions
  - Structural fire engineers should be adequately experienced to identify the assumptions and approximations embedded within the software including its limitations.











Summary

- **Structural Fire Engineering**
  - Fire is one of the severe disasters that cause a great loss of life and property.
  - Purkiss (2007) :
    - *"The application of scientific and engineering principles to the effects of fire in order to reduce the loss of life and damage to property by quantifying the risks and hazards involved and provide an optional solution to the application of preventive or protective measure."*

- **Structural Fire Design in Codes and Standards**
  - Assessment methods of fire resistance in time, temperature, and strength domains
  - Fire-resistance rating requirements for building elements based on construction type and occupancy
  - Reviewed the prescriptive method and calculation method in IBC
  - Also reviewed the simple calculation method in EUROCODE 2/3/4

- **Advanced Structural Fire Design**
  - Drawbacks of the current design method based on the prescriptive approach
  - Process of performance-based structural fire design
  - Reviewed the options for heat transfer and structural analysis
  - Possibility of structural assembly and whole building behavior analysis using advanced models

References

Codes & Standards

- ACI 216.M-07, Standard Method for Determining Fire Resistance of Concrete and Masonry Construction Assemblies
- AISC 360-16, Specification for Structural Steel Building
- ASCE/SFPE 29-05, Standard Calculation Methods for Structural Fire Protection
- Eurocode 1, Actions on Structures, Part 1.2: General Actions - Actions on Structures Exposed to Fire
- Eurocode 2, Design of Concrete Structures, Part 1.2: General Rules-Structural Fire Design
- Eurocode 3, Design of Steel Structures, Part 1.2: General Rules-Structural Fire Design
- Eurocode 4, Design of Composite Steel and Concrete Structures, Part 1.2: General Rules-Structural Fire Design
- International Building Code
- ISO 834-1: Fire Resistance Test–Elements of Building Construction
- NFPA 5000, Building Construction and Safety Code

Books

- Andrew H. Buchanan, Structural Design for Fire Safety
- IStrucE, Guide to the advanced fire safety engineering of structures
- SFPE Handbook of Fire Protection Engineering
- Y.C. Wang, Steel and Composite Structures: Behavior and Design for Fire Safety

Modernization of Uzbekistan Building Code (UBC) System

Thank you

국토교통부
Ministry of Land, Infrastructure and Transport

해외건설협회
International Contractors Association of Korea

KICT
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서울시립대학교
UNIVERSITY OF SEOUL

RICON
KOREA RESEARCH INSTITUTE FOR CONSTRUCTION POLICY