Fire Safety Design for Building
- Fire Resistance Verification Method-

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Outline

- Trend of Building Fire in Japan
- Performance Based Code
- Framework of Evaluation on Fire Safety under Performance Based Code
- Fire Safety Verification Methods of Building Standards Law of Japan
- Examples of Design and Research
1. Trend of Building Fire in Japan

- Fire Damage since 1946
- Trends in dwelling fires
- Fatalities by aged groups in dwelling fires
- Major fire causes
Fire Damage since 1946

![Graph showing the number of building fires and fatalities over the years from 1946 to 1996.](image-url)

- **Number of building fires**
  - Y-axis: Number of fires (0 to 50,000)
  - Data trends indicate an overall increase in the number of fires from 1946 to 1971, followed by a decrease until 1996.

- **Number of fatalities**
  - Y-axis: Number of fatalities (0 to 5,000)
  - Data trends show a steady increase from 1946 to 1971, with fluctuations in subsequent years, culminating in a peak in 1991.
Trends in dwelling fires

No. of fires
- 1998: 18,895
- 1991: 19,531

No. of fatalities
- 1998: 865
- 1991: 923

No. of aged fatalities
- 1998: 449
- 1991: 458

1991 vs 1998:
- Cases: Decrease
- Persons: Decrease
- Highelderly:
  - Cases: Decrease
  - Persons: Decrease
Fatalities by aged groups in dwelling fires

Rate of fatalities per 100,000 people

Little children  Aged people

(注) 年齢不明者5名を除く。人口は、平成10年10月1日現在の推計人口（総務庁統計局）による。
Major fire causes

Exhibit 11 Number of fires and amount of damage by cause (1997)

- Arson: 7,222 fires
- Smoking: 12,599 fires
- Kitchen range: 5,893 fires, 11,791 damage
- Suspected arson: 5,654 fires, 11,659 damage
- Bonfire: 2,528 fires
- Playing with fire: 2,964 fires, 2,727 damage
- Heater: 1,905 fires, 10,340 damage
- Kindling: 1,370 fires, 993 damage
- Electric light and telephone wiring: 1,282 fires, 5,449 damage
- Incinerators: 1,113 fires, 2,072 damage
- Matches and lighters: 1,069 fires, 1,633 damage
- Electric equipment: 981 fires, 4,884 damage
- Wiring equipment: 830 fires, 4,632 damage
- Exhaust pipes: 781 fires, 493 damage
- Welding and cutting machines: 760 fires, 2,382 damage
- Bath furnaces: 674 fires, 1,564 damage

No. of fires
Amount of damage

(¥ million)
2. Performance Based Codes

- Performance Based Codes
  (Nordic Committee on Building Regulation 5 Level System)
System of Performance Based Code (NKB 5 Level System)

- Objective
  - Functional Requirements
  - Performance Requirements
  - Specification

- Life Safety
  - Provision of Egress Means
    - Safety from Smoke
      - Limitation of height of Smoke Layer
        - Standards, Guide
          - Eng. Tools (Simulation, Experiments)
  - Verification Methods
  - Eng. Tools
3. Framework of Evaluation on Fire Safety under Performance Based Code

- Framework of evaluation on Fire Safety under performance based code
Framework of evaluation on Fire Safety under performance based code

Objective

- Reduction of fire occurrence
- Evacuation safety
- Prevention of structural collapse
- Assurance for fire fighting
- Prevention of urban fire

Occupancy of Fire Confinement
Performance of envelope

Calculation of design fire

Can envelope endure design fire?

No

Yes
Design Fire

- Reduction of fire occurrence
- Prevention of structural collapse
- Evacuation safety
- Prevention of urban fire

To the Framework of evaluation
Feedback for Design Fire

- Assume the envelope’s insulation and integrity performance
  - Fuel load (occupancy dependent)
  - Lining Materials
  - Ventilation

Simulation by Design Fire

“Heat and/or Flame interruption fails.”

Yes

No
Feedback for design fire (returns)

\[ Q_f = \alpha t \]

bound by fuel surface area

\[ Q_f = 100 A_{\text{fuel}} \]

bound by ventilation

\[ Q_f = 1500 A_w \sqrt{H_w} \]

sum of combustion heat in fire compartment

\[ L_{wwall} A_{wall} \]

\[ \sum L_{wwall} A_{wall} \]
Evaluation of Structural Fire Resistance

- Sufficient Stability of Building Frames during fire

Check by

- whole structural frame
- or
- individual load bearing elements
Evaluation Model for Structural Fire Resistance (Load Bearing)

Fuel load → Design fire temperature → Strength reduction

Opening size → Design fire temperature

Compartment characteristics → Design fire temperature

Building frame design → Service load

Fuel load: Duration of fire

Opening size: Impact on heat transfer

Compartment characteristics: Temperature distribution

Building frame design: Load-bearing capacity in service

Strength reduction: Decrease in structural strength over time

Heat impact: Effect of heat on material properties
Design Fire → Room Temperature

Design fire

Room temperature

Fire duration
Evaluation of Structural Fire Resistance
Evaluation of Evacuation Safety

- Evacuation to the staircase

1. Smoke propagation and its control
2. Detection and alarm
3. Reaction (time lag until escape starts)
4. Escape movement
Evaluation of Evacuation Safety

3. Reaction

Estimate smoke leakage by interruption performance
Evaluation of Evacuation Safety

4. Escape movement
Reduction of Fire Occurrence

- Prevention of fire initiation under daily heat source

1. Initiation model under daily heat source
2. Design for interior furnish

Do not outspread to the whole room

Yes
No
Ordinary fire source

- Example: No materials should be ignited by radiation from a cooking stove.
Example: Deep fry oil fire caused by over heating ("Tempura" fire)
Prevention of fire spread to/from neighbors

- Prevention of fire spread to/from neighbors

1. Fire model of outspread buildings to buildings

2. Design for exterior
Basic concept on Prevention of fire spread

Quasi-Fire Zone

Allowed fireproof, quasi-fireproof, and fire preventive construction

Don’t ignite wood houses.
Basic concept on Prevention of fire spread

Quasi-Fire Zone

Allowed fireproof, quasi-fireproof, and fire preventive construction

Fire resistant wall more than 30 min.
4. Fire Safety Verification Methods of Building Standards Law of Japan

- Fire Resistance Verification Method
- Fire Compartment Verification Method
- Verification Method for Floor Evacuation safety
- Verification Method for Building Evacuation safety
Definition of Fire Resistive Building in BSLJ 1/

- (a) Major structural elements of the building are either
  - (1) fire resistant constructions, or
Definition of Fire Resistive Building
in BSLJ 2/

– (2) those elements that comply with the following performance requirements:

- (i) A building shall resist expected indoor fires, corresponding to the construction and service equipment of the building, throughout their duration.
- (ii) A building should resist ordinary fires occurring in the neighbor of the building throughout their duration.
(b) An opening of an exterior wall that is susceptible to the spread of fire from adjacent buildings shall be constructed with a fire door or other fire preventive equipment.
Performance requirements of BSLJ

For indoor fires:

<table>
<thead>
<tr>
<th></th>
<th>Ext. Wall</th>
<th>Partition Wall</th>
<th>Column</th>
<th>Beam</th>
<th>Floor</th>
<th>Stairs</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loadbearing capacity</td>
<td>r*</td>
<td>r*</td>
<td>r</td>
<td>r</td>
<td>r</td>
<td>r</td>
<td>r</td>
</tr>
<tr>
<td>Integrity</td>
<td>r</td>
<td></td>
<td>r</td>
<td></td>
<td></td>
<td>r</td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td></td>
<td></td>
<td>r</td>
<td></td>
<td></td>
<td></td>
<td>r</td>
</tr>
</tbody>
</table>

r: required, r*: required only for load bearing walls

For neighbor fires:

<table>
<thead>
<tr>
<th></th>
<th>Ext. Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loadbearing capacity</td>
<td>r*</td>
</tr>
<tr>
<td>Insulation</td>
<td>r</td>
</tr>
</tbody>
</table>

r: required, r*: required only for load bearing walls
Performance Criteria

- For indoor fires:(expected fire)
  - fire resistance time $\geq$ duration of fire.

- For neighbor fires:(standard fire)
  - fire resistance time of an exterior wall $\geq$ prescribed time (60 or 30 minutes)
Applicability and Features of the Verification Method

- Applicable to steel, reinforced concrete and wood structured buildings
- Evaluation process of expected indoor fire is common to all types of structures
- Determination process of fire resistance time differs among structures
Steel

- Applicable only to columns and beams of moment resisting steel frames
- Applicable to unprotected members and members protected with sprayed rockwool or calcium silicate boards
- Only for loadbearing capacity verification
Reinforced Concrete

- Applicable to columns, beams, walls, slabs and roofs
- Ordinary concrete or Class 1 light weight concrete
- Design strength of concrete not exceeding 60 MPa
- Loadbearing capacity, insulation and integrity can be verified
Wood

- Applicable only to columns and beams
- Minimum section size not less than 20 cm
- Only for loadbearing capacity verification
Extraction of a Fire Compartment

Stress of an Element due to Sustained Loads

Total Heat Release $Q_r$
Incl. Heat Intrusion from Adjacent Rooms

Heat Release Rate $q_b$

Fire Severity Parameter $\alpha$

Severity Parameter of Proximity Fire $\alpha_f$

Fire Resistance Time of an Element $t_{fr}$

Fire Duration $t_f$

$\sqrt{t_{fr}} \geq t_f$

END
Fire Duration and Fire Severity

- **Total Heat Release (MJ)**

\[ Q_r = q_l A_r + \sum q_f A_f d_f + \sum f_a \left( q_{la} A_{ra} + \sum q_{fa} A_{fa} d_{fa} \right) \]
## Values of Fuel Load

<table>
<thead>
<tr>
<th>Room Use</th>
<th>$q_i$ (MJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential Room</td>
<td>720</td>
</tr>
<tr>
<td>Guest Room of Hotel</td>
<td>240</td>
</tr>
<tr>
<td>Office</td>
<td>560</td>
</tr>
<tr>
<td>Meeting Room</td>
<td>160</td>
</tr>
<tr>
<td>Seating Space of Theater or Assembly</td>
<td>240</td>
</tr>
<tr>
<td>Stage of Theater or Assembly</td>
<td>480</td>
</tr>
<tr>
<td>Classroom</td>
<td>400</td>
</tr>
<tr>
<td>Selling Floor of Department Store</td>
<td>480</td>
</tr>
<tr>
<td>Seating Space of Restaurant</td>
<td>480</td>
</tr>
<tr>
<td>Storage</td>
<td>2,000</td>
</tr>
</tbody>
</table>
Heat Release Per Unit Area, Per Unit Thickness of Interior Finish

<table>
<thead>
<tr>
<th>Material Classification</th>
<th>Heat Release $q_f$ (MJ/m²/mm)</th>
<th>Oxygen Consumption Coefficient $\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noncombustible</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Fire Retardant</td>
<td>1.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Slow Burning</td>
<td>3.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Others</td>
<td>8.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
# Heat Intrusion Factor

<table>
<thead>
<tr>
<th>Construction of Wall or Floor</th>
<th>Fire Preventive Equipment</th>
<th>Heat Intrusion Factor $f_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Resistive Construction</td>
<td>Special Fire Preventive Equip.</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Fire Preventive Equip.</td>
<td>0.07</td>
</tr>
<tr>
<td>Specified Quasi Fire Resistive Construction</td>
<td>Special Fire Preventive Equip.</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Fire Preventive Equip.</td>
<td>0.08</td>
</tr>
<tr>
<td>Quasi Fire Resistive Construction</td>
<td>Special Fire Preventive Equip.</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Fire Preventive Equip.</td>
<td>0.09</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td>0.15</td>
</tr>
</tbody>
</table>
Heat Release Rate

\[ q_b = A_{fuel} \cdot \begin{cases} 
1.6 \chi & (\chi \leq 0.081) \\
0.13 & (0.081 < \chi \leq 0.1) \\
2.5 \chi \exp(-11\chi) + 0.048 & (0.1 < \chi)
\end{cases} \]

\[ \chi = \max \left[ \sum A_{op} \frac{\sqrt{H_{op}}}{A_{fuel}}, \frac{A_r \sqrt{H_r}}{70 A_{fuel}} \right] \]
Duration of fire

\[ t_f = \frac{Q_r}{60q_b} \]

Fire temperature curve for the compartment

\[ T_f(t) = \alpha t^{1/6} + 20 \quad (0 \leq t \leq t_f) \]
Fire Severity Parameter

Fire severity parameter

\[ \alpha = 1280 \left( \frac{q_b}{\sqrt{\sum A_C I_h \sqrt{f_{op}}}} \right)^{2/3} \]

Opening factor

\[ \sqrt{f_{op}} = \max \left[ \sum A_{op} \sqrt{H_{op}}, A_r \sqrt{H_r} / 70 \right] \]
Fire Resistance Time of Steel Columns

The critical temperature of a steel column, $T_{cr}$ (°C), is:

$$T_{cr} = \min\{T_B, T_{LB}, T_{DP}, 550\}$$

where

- $T_B$: Temperature of overall buckling (°C)
- $T_{LB}$: Temperature of local buckling (°C)
- $T_{DP}$: Limit temperature for deformation (°C)
- 550: Limit temperature for joint stability (°C)
Overall Buckling

For \( \lambda < 0.1 \):

\[
T_B = 700 - 375p
\]

and for \( 0.1 \leq \lambda \leq 1 \):

\[
T_B = \max \left\{ 700 - 375p - 55.8(p + 30p^2)(\lambda - 0.1), 500\sqrt{1 - \frac{p(1 + 0.267\lambda^2)}{1 - 0.24\lambda^2}} \right\}
\]
\[ T_{LB} = 700 - \frac{375 \ p}{\min(R_{LBO}, 0.75)} \]
<table>
<thead>
<tr>
<th>Section Shape</th>
<th>$R_{LBO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide Flange</td>
<td>$\min \left{ \frac{7}{0.72 \frac{B_f}{t_f} + 0.11 \frac{B_w}{t_w}} \right}, 21 \frac{t_w}{B_w}$</td>
</tr>
<tr>
<td>Square or Rectangular Tubing (Hot-formed or Weld</td>
<td>$21 \frac{t}{B}$</td>
</tr>
<tr>
<td>Built-up)</td>
<td></td>
</tr>
<tr>
<td>Cold-formed Square or Rectangular Tubing</td>
<td>$17 \frac{t}{B}$</td>
</tr>
<tr>
<td>Pipe</td>
<td>$\frac{35.6}{D/t_cy} + 10.6$</td>
</tr>
</tbody>
</table>

$B_f$, $B_w$, $t_f$, $t_w$, $B$, $t$, $D$ and $t_cy$ are measured in mm.
Deformation Limit

\[ T_{DP} = 20 + \frac{18000}{\sqrt{A_r}} \]
Fire Resistance Time

\[
t_{fr} = \max\left\{ \frac{9866}{\alpha^{3/2}} \left\{ \frac{2}{h} \log_e \left\{ h^{1/6} (T_{cr} - 20)/1250 \right\} \right\}^2 + \frac{a_w}{(H_i/A_i)^2} \frac{1}{\left( \frac{T_{cr} - 20}{\alpha} \right)^6} \right\}
\]
For protected steel sections the temperature rise parameter of the sections, \( h \), is:

\[
h = \frac{\psi K_0 \left( \frac{H_s}{A_s} \right)}{\left\{ 1 + \frac{\psi R}{H_i / A_i} \right\} \left\{ 1 + \frac{\psi}{2} \frac{H_s / A_s}{H_i / A_i} C \right\}}
\]
Yield Strength of Steel at Elevated Temperature

![Graph showing yield strength as a function of temperature]

- The graph plots the yield strength, $\sigma_y(T)$, on the Y-axis against temperature, $T$ (°C), on the X-axis.
- The yield strength remains constant up to a temperature of 325 °C, and then it decreases linearly until 700 °C.
5. Examples of Design and Research

- Fire Safety Measures Applied to New Office of Shimizu Institute of Technology
- Fire Resistance Test of Steel Column
Fire Safety Measures Applied to New Office of Shimizu Institute of Technology

External Appearance
Fire Safety Measures Applied to New Office of Shimizu Institute of Technology

Elements without Fire Protection Covering
Fire Safety Measures Applied to New Office of Shimizu Institute of Technology

Before Fire

After Fire
Fire Safety Measures Applied to New Office of Shimizu Institute of Technology

Frame without Fire Protection Covering Compartment of Elevator Hall using Water Curtain
Fire Safety Measures Applied to New Office of Shimizu Institute of Technology

Seismic Isolation Device without Fire Protection Covering
Fire Resistance Test of Steel Column

Column Furnace

Test Specimen
Fire Resistance Test of Steel Column

Heating Curves

![Graph showing heating curves for ISO 834 Std. and Hydrocarbon. The graph plots Time (min.) on the x-axis and Temperature (Deg.C) on the y-axis. The ISO 834 Std. curve is represented in red, while the Hydrocarbon curve is in blue. The graph shows the temperature increasing with time.]
## Fire Resistance Test of Steel Column
### Summary of Experiments

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Grade</th>
<th>Protection (Fireguard®)</th>
<th>Load Load ratio</th>
<th>Heating</th>
<th>End of the Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SN490C</td>
<td>80 mm (3-hour-rated)</td>
<td>10.1 MN (0.5)</td>
<td>Hydrocarbon</td>
<td>3 hours</td>
</tr>
<tr>
<td>1A</td>
<td>SN490C</td>
<td>80 mm (3-hour-rated) 25% unprotected</td>
<td>10.1 MN (0.5)</td>
<td>Hydrocarbon</td>
<td>Deformation reversal (27.5 min.)</td>
</tr>
<tr>
<td>2</td>
<td>SN490C</td>
<td>30 mm (1-hour-rated)</td>
<td>9.8 MN (0.49)</td>
<td>ISO-834</td>
<td>Deformation reversal (330min.)</td>
</tr>
<tr>
<td>3</td>
<td>NSFR490C</td>
<td>30 mm (1-hour-rated)</td>
<td>12.9 MN (0.6)</td>
<td>ISO-834</td>
<td>4 hours</td>
</tr>
<tr>
<td>3A</td>
<td>NSFR490C</td>
<td>30 mm (1-hour-rated) 25% unprotected</td>
<td>6.5 MN (0.3)</td>
<td>ISO-834</td>
<td>Deformation reversal (105min.)</td>
</tr>
</tbody>
</table>
Fire Resistance Test of Steel Column
Removal of Protection

Fully protected

→ 25% Unprotected
Fire Resistance Test of Steel Column
Comparison of Steel Temperatures

Fully protected

25% unprotected
Fire Resistance Test of Steel Column

Column Elongations vs. Time

Exp. 1
Exp. 1A
Exp. 2
Exp. 3
Exp. 3A

3h-rated; 25%UP Hydrocarbon
1h-rated; FP standard
3h-rated; FP Hydrocarbon

Displacement (mm)

Time (min.)