Fire performance of structures

John Hewitt
Structures and Fire

- Structural design
- Structural engineers, Fire engineers
- Concepts for structural assessment in Fire
- Fire severity
  - Time equivalence
  - Other approaches
  - Comparisons
Structural Design
Structural Design

- Loads are relatively well understood and/or defined in standards
- Loads are subject to factors of safety
- Expected strengths and member capacities are reduced by factors
- All structural materials are tested
- Each structural member is specifically designed for forces upon it, taking into account its role in the overall structure
- Structural engineers understand ‘load paths’ and how every force can be resisted and transferred to the ground
Structural design

... but there are many uncertainties

• Dead loads, live loads, wind loads
• Seismic and fire – analogy – extreme cases
• Both push the structural performance beyond normal limits, allowing yield, and damage to occur
• In seismic design, very important to understand the structural performance, dynamics, non-linear behaviour etc
• Need similar understanding in a structural fire case to check that performance will be achieved
For buildings that would require Type A construction:

- No collapse of main structure, with full burn out
- No breach of compartmentation
- Usually no active systems or intervention assumed
Do structural engineers understand fire?

• Fire is not usually part of a structural engineers training (we are working on this!)

• FRL, fire severity, not understood fully or not at all

• BCA is rarely looked at

• But on being told a required FRL, structural designers will apply code rules for concrete dimensions, cover etc

• Loading standards specify a ‘Fire Load case’, ie a reduced vertical load to be supported in the case of a fire.

• For steel, can work out a ‘critical temperature’, for single elements.

• Fire performance of whole structure needs specialised knowledge
Do fire engineers understand structures?

- ??

- Conclusion: In assessing fire performance of structures, there are gaps in the usual understanding of the main players.
Concepts for structural fire performance
Structural Performance in fire – ideal performance:

For buildings that would require Type A construction:

- No collapse of main structure, with full burn out
- No breach of compartmentation
- Usually no active systems or intervention assumed
Fire Protection for single steel elements

- How hot can the steel be allowed to reach, and still carry prescribed loads?
- How long must it remain below this temperature i.e. what is the required FRL?
- What protection is required to do this?
Steel - Reduction in strength and stiffness

Curve 1: Yield stress ratio
Curve 2: Modulus of elasticity ratio

YIELD STRESS RATIO OR MODULUS OF ELASTICITY RATIO

STEEL TEMPERATURE (\(T\)), °C
Load Cases – AS 1170.0

- Normal Load case: 1.2 Dead + 1.5 Live
- Fire Load case: 1.0 Dead + 0.4 or 0.7 Live

- Load factors reduced

- eg If dead = Live
- If 90% utilization for NLC
- \( r = 0.9 \times \frac{FLC}{NLC} = 0.9 \times \frac{1.4}{2.7} = 0.47 \)
- \( T_{crit} = 905 - 690r \)
- Critical temperature = 583°C
Critical Temperature

- 550°C often used as a criterion for fire protection materials
- But Critical temperature could be less – eg if mostly dead load
- Or could be more, eg if structure has spare strength under normal loads
- So need to check it
How quickly does steel heat up?

Depends on:

- Gas temperature
- Exposed area
- Thermal Inertia
- Insulation
**K_{sm} Concept**

- Exposed surface area to mass ratio $m^2$/tonne


classic figure

High $K_{sm}$
heats quickly

Low $K_{sm}$
heats slowly

- Some codes use Heated Perimeter/Area $H_p/A$
  - (deals with the same thing)
Composite construction – interaction of elements

For composite construction:

- Some secondary beams left unprotected
- Columns and their connections should be protected
- Floor slab is key to increased strength in fire conditions
- Detailed numerical models
Importance of the slab

- Anchoring tensile membrane action around the perimeter edge of the slab
- Composite edge beams
- Anchoring reinforcing mesh

Compression (thermal pre-stressing effect) at the boundaries

Tensile membrane action in the interior anchored by the boundary compression
Heron Tower

Compartment floor

Atrium floors

Typical Village
Design fire protection layout

- 20 mm glass fibre reinforced gypsum board
- 120 min intumescent paint along gridline K
- Typical low rise core
- Columns in core area protected to 90 minutes
- Village Floor
One Shelley Street
One Shelley Street

Floor beams 60/-/-
Unprotected beams
Floor slabs 120/120/120
Diagrid 60/-/-
Internal columns 120/-/-
Cores 120/120/120
Material Response - Timber

Charring and heat affected zone, deeper with time, insulates inner timber

Eg 0.7mm/min +7.5 mm

Calculate the strength based on what's left
Material Response - Concrete

- Heat transfer to other side – fire separation
- Heat transfer to steel
- Concrete degrades, may spall
Fire Severity
Time-Equivalent Analysis
The more ventilation the lower the temperature so a lower rating possible

Ventilation - 60 v’s 120 minutes
Fire severity – time equivalence calculation

**Equivalent Time of Exposure to Standard Furnace Test from Eurocode 1 and CIBSE Guide E**

### Input

<table>
<thead>
<tr>
<th>Room parameters</th>
<th>Building design and use parameters</th>
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<tbody>
<tr>
<td>Depth = 15.0 m</td>
<td>Fuel load = 1040 MJ/m²</td>
</tr>
<tr>
<td>Width = 23.5 m</td>
<td>Conversion factor (k_v) = 0.07</td>
</tr>
<tr>
<td>Height = 3.8 m</td>
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</tr>
<tr>
<td>Floor area = 352.5 m</td>
<td></td>
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</tbody>
</table>

### Vertical Opening Details

<table>
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<tr>
<th>Number</th>
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### Results

- \(A_i = 997.6 \text{ m}^2\) Total surface area
- \(A_v = 89.3 \text{ m}^2\) Area of ventilation
- \(h = 3.8 \text{ m}\) Equivalent height of openings

\[\alpha_v = 0.25 \quad 0.025 < \alpha_v < 0.25\]
\[\alpha_h = 0.00\]
\[b_v = 43.36 \quad b_v > 10\]
\[w_t = 0.76\]

<table>
<thead>
<tr>
<th></th>
<th>Eurocode method</th>
<th>BS 9999 method</th>
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<tr>
<td>Equivalent time of exposure</td>
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### Fire severity – time equivalence calculation

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<th>Inputs</th>
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<tr>
<td>average dims</td>
<td>$\alpha_v = 0.25333$</td>
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<td>$\alpha_h = 0$</td>
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<td>Floor area</td>
<td>$b_v = 43.4$</td>
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<tr>
<td>Height to roof</td>
<td>$w_f = 0.759 \text{ m}^{-0.3}$</td>
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<td>Area of wall openings</td>
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<td>$k_b$</td>
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<td>window height</td>
<td>$3.8 \text{ m}$</td>
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Time equivalence – Eurocode formula

\[ t_e = k_h \ w \ Q_f \]  

(3)

where \( k_h \) (min m\(^2\)/MJ) replaces \( e \) and the ventilation factor \( w \) is altered to allow for horizontal roof openings, given by:

\[ w = \left( \frac{6.0}{H_c} \right)^{0.3} \left[ 0.62 + \frac{90(0.4 - \alpha_v)}{1 + b_v \alpha_h} \right] > 0.5 \]  

(4)

where: \( H_c \) is the compartment height (m)

\[ \alpha_v = A_v / A_f \quad 0.05 \leq \alpha_v \leq 0.25 \]  

(5)

\[ \alpha_h = A_h / A_f \quad \alpha_h \leq 0.20 \]  

(6)

\[ b_v = 12.5 \ (1 + 10 \ \alpha_v - \alpha_v^2) \]  

(7)

\( A_f \) is the floor area of the compartment (m\(^2\))

\( A_v \) is the area of vertical openings (m\(^2\))

\( A_h \) is the area of horizontal openings (m\(^2\))
Time equivalence calculations – pros and cons

Pros

• Recognises effect of fuel load, ventilation, compartment dimensions and boundary conditions
• Simple to calculate, simple to use the result

Cons

• Black box calculation
• Does not convey understanding of the nature of the fire
• Cannot separate short/hot fires from longer cooler fires
• Does not understand different structures, different critical temperatures, different structural performance
• Developed for protected steelwork, not concrete, timber, insulation issues etc
A more rigorous approach
Time temperature model
• Parametric fire
• CFD calc
• Test measurements

Heat transfer model
• Radiation, convection, conduction
• 1-dimensional – lumped mass
• 2-d or 3-d heat transfer – finite elements
• Thermal properties constant or vary with time/temp

Structural model
• Single element strength v temperature
• Interaction with whole building
‘Slimflor’ system
Finite Element Model
Temperature and strength at 60 minutes

Upper flange, 100°
Strength 100%

Lower flange, 600°
Strength 40% approx

Overall plastic moment capacity, x 80% approx
1 dimensional assessment

- Protected steelwork – specific sections
- Time in a standard fire to cause same reduction in strength as predicted actual fire
- Critical temperature
The effect of ventilation
Comparison case – 60 minutes equivalent FRL

Equivalent Time of Exposure to Standard Furnace Test
from Eurocode 1 and CIBSE Guide E

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Test case 60 FRL – compare using parametric fire, simple 1d heat transfer

410 x 60kg/m Universal beam, with fire protection for 60 FRL, 19mm insulation, critical temperature 550°C
Parametric fire curve generated from same room/fuel data
410UB with protection FRL60, max temp = 493°C < Tcrit
How about a much smaller steel section?

150 UB14 FRL60, 27mm insulation, max temperature 502°C
Hot and fast or longer slower fire?

### Eurocode Time-temperature curve

![Eurocode Time-temperature curve](image)

### Eurocode EC1 (1994)

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<td>Height to roof</td>
<td>$w_\gamma$ = 2.144 m$^{0.3}$</td>
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<td>Area of wall openings</td>
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Long slow fire

410UB, long slow fire with T equiv = 60 min, max temp = 532°C
400 dia concrete column

Parametric fire

ISO fire

Outer surface

Inner core
Structural Fire Design: The Role of Time Equivalence

G.C. THOMAS, A.H. BUCHANAN and C.M. FLEISCHMANN
University of Canterbury
FIGURE 3. Time temperature curves from COMPF-2 assuming pessimized

FIGURE 10. Finite element grid for protected steel column (one quarter).
FIGURE 11. Comparison of calculated time equivalent with Eurocode formula for concrete members.

FIGURE 12. Comparison of calculated time equivalent with Eurocode formula for steel members.
FIGURE 13. Comparison of calculated time equivalent with Eurocode formula for insulation failure of timber joist floors.

FIGURE 14. Comparison of calculated time equivalent with Eurocode formula for structural failure of light timber walls.
Fire Severity - Summary

- Time equivalence calcs can be useful, but care needed to apply only when valid
- T equiv not useful for detailed structural fire assessment beyond applying FRL
- Concerns in a number of cases, eg short fires, cases other than protected steel structure
- More rigorous approach is possible, even with the same input data, that can provide better insight into performance and uses specific properties of the structure