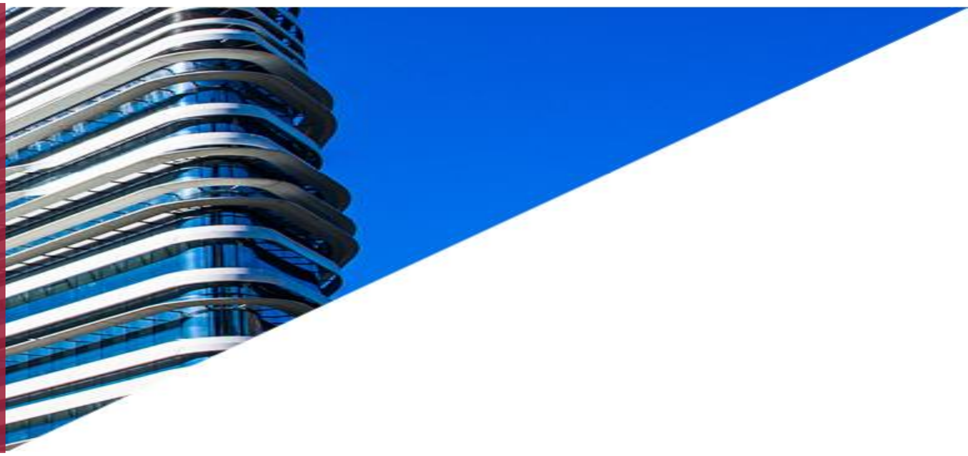
THE HONG KONG POLYTECHNIC UNIVERSITY 香港理工大學
FACULTY OF CONSTRUCTION AND ENVIRONMENT 建設及環境學院
Department of Building Environment and Energy Engineering 建築環境及能源工程學系
Research Center for Fire Safety Engineering 火災安全工程研究中心

12th International Conference on Structures in Fire SiF2022, Hong Kong



OpenSees Workshop

Modelling timber structural members in fire

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Conflicts in using timber material

Mjosa Tower, Norway [1]


T3 Office Building , United States [2]

Sustainability and aesthetics

Global Carbon Neutrality

Green City

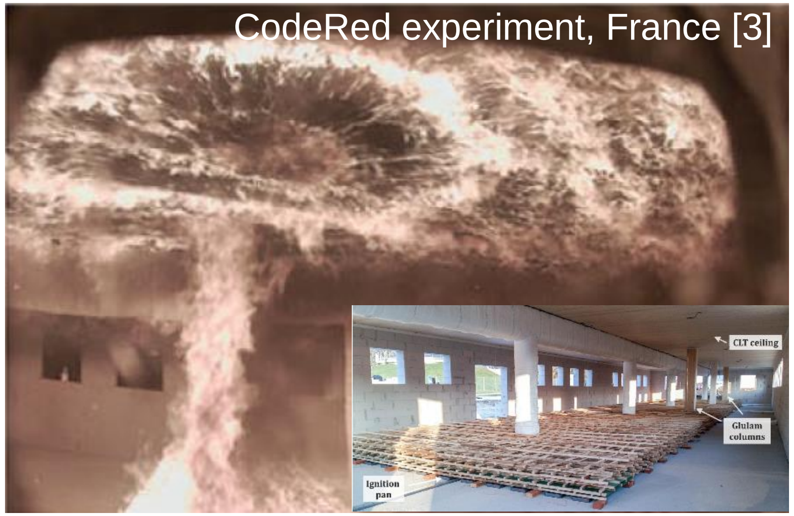
} **Potential**

Barrier {

Flammability characteristics

Additional fire load

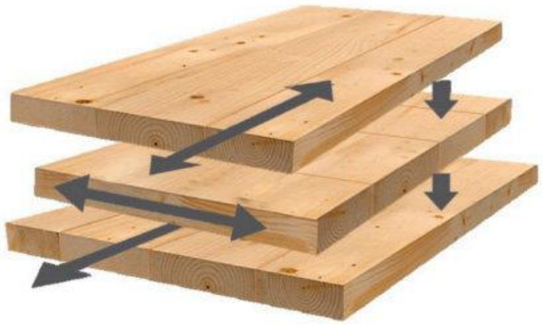
Fire safety problems



CodeRed experiment, France [3]


Motorcycle museum, Australia [4, 5]

Cross-laminated timber (CLT)



Cross-laminated timber [6]

- Odd layer with symmetry

- Uniform strength properties (Elimination of defects in individual timbers)
- Good earthquake-resistant performance (light weight)
- Better acoustic performance
- Thermal insulation and humidity regulation
- Prefabricated components (cost-efficient)

? Fire resistance? (Naturally combustible properties)

↓

Mainly based on test

↓ ← High test cost, large investment of human, time consumption

Numerical simulation

↓

Open System for Earthquake Engineering Simulation (OpenSees)

↓

OpenSees for fire
(Purposed for modelling structures in fire)

- Material library, element types
- Nonlinear processing, static and dynamic analysis, and structural section research
- Faster calculation
- High simulation accuracy
- Easy convergence in the analysis of complex structures

Process of modelling timber members in fire

(1) Heat transfer model for timber → Heat transfer analysis → Thermal responses (Temperature distribution, char depth and layer distribution)

Thermal load

(2) Constitutive model for timber → Static load analysis at ambient temperature → Thermo-mechanical responses (Stress-strain curve and deformation)

Assignments:

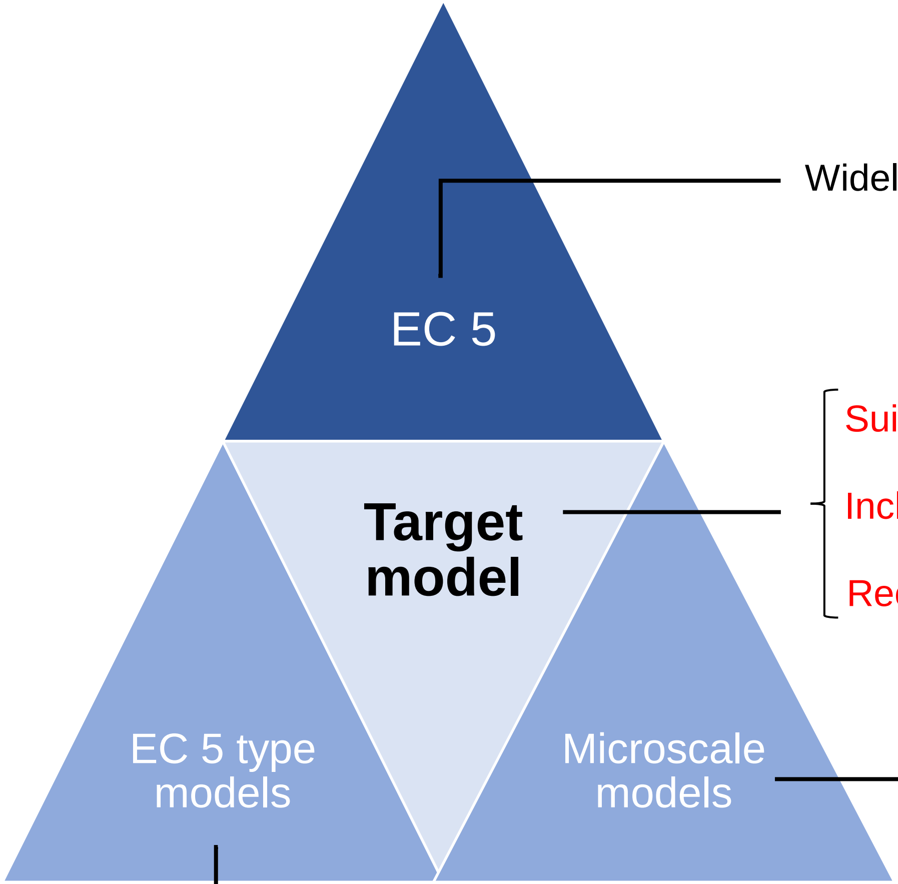
Develop the heat transfer model for timber **(TimberHTMatrial)**

Develop the constitutive model for timber **(TimberECThermal)**

Contents

- **Development** of layer-based heat transfer model for timber in fire
  - Case 1: Timber section exposed to fires
- **Development** of thermo-mechanical model for timber members in fire
  - Constitutive model for timber
  - Mechanical properties of timber at elevated temperature
  - Zone-based thermal action for timber beams
  - Modelling procedure in OpenSees for fire for timber members in fire
  - Case 2: Fire resistance of timber members exposed to fires
- **Demonstration**
  - Case 3: The composite member (Timber concrete composite floor system, TCC) in realistic fire scenarios

1. Development of layer-based heat transfer model for timber in fire



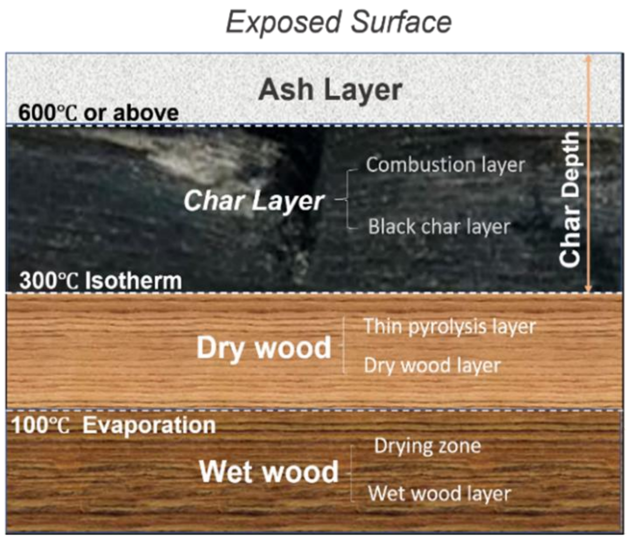
Widely adopted:
- Specific heat model only considers heat consumption
- Recommended for **standard fire** cases only

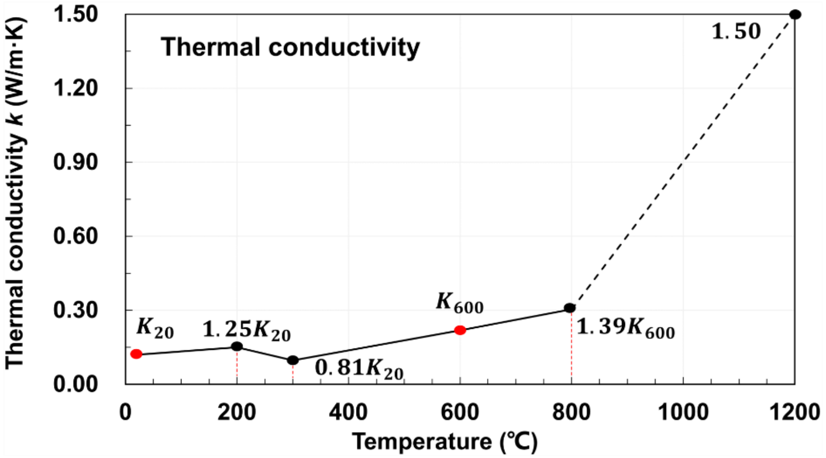
Layer-based heat transfer model
- Suitable for non-standard fire scenarios
- Include heat effect due to timber combustion
- Record real-time layer state. It can re-enter charring after cooling

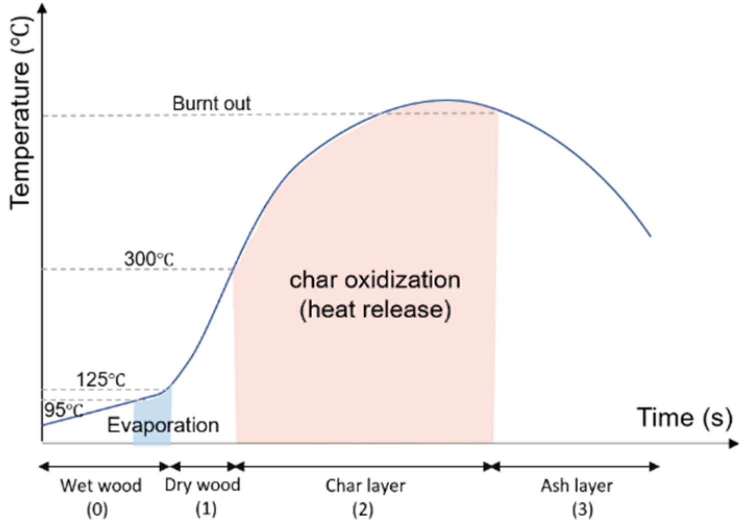
- Very detail model: Gpyro model
- Not easy to integrate with FEM tool

Modified from EC5 model, without heat generation

1. Development of layer-based heat transfer model for timber in fire







☐ Layer model

- Wet wood
- Dry wood
- Char layer
- Ash layer

☐ Layer thermal properties model (k, ρ, C_p)

- Temperature dependent
- Layer state dependent

☐ Charring heat model

- During the timber charring
- Releasing heat
- Most heat to environment

Case 1 – Timber section exposed to fires

Tcl interpreter

↓

Heat transfer module

↓

Mesh tool

↓

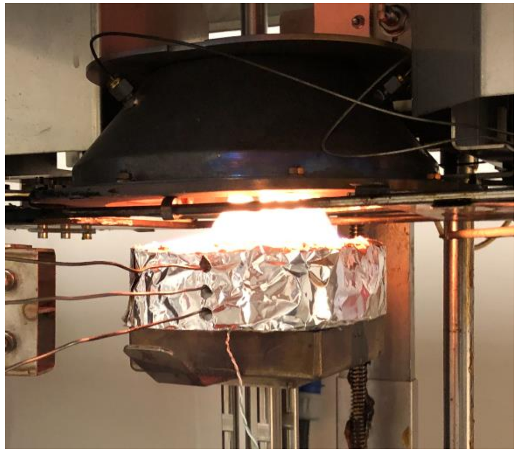
HTDomain

HT_Materials

HT_Elements

HT_BC

HT_Analysis

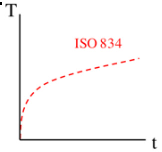


Parameters for modelling thermal response of Timber sections:

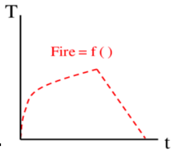
- Element Size
- Moisture content
- Density

Fire model library

Idealised Uniform Fires

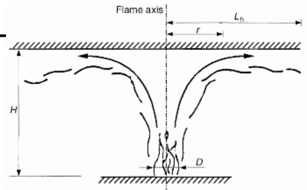


Standard fire

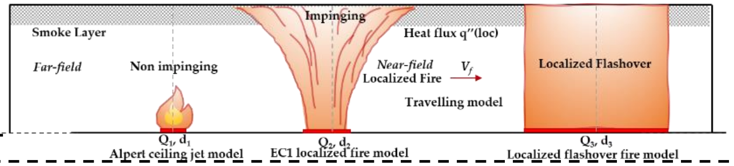


Parametric fire:
More parameters considered: fuel load, ventilations and compartment dimensions

Idealised Non- Uniform Fires

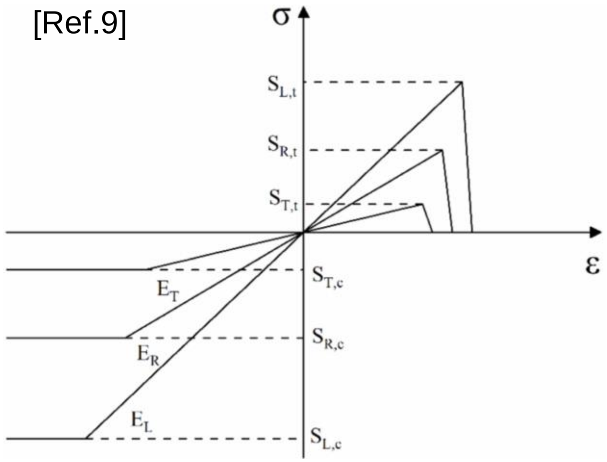


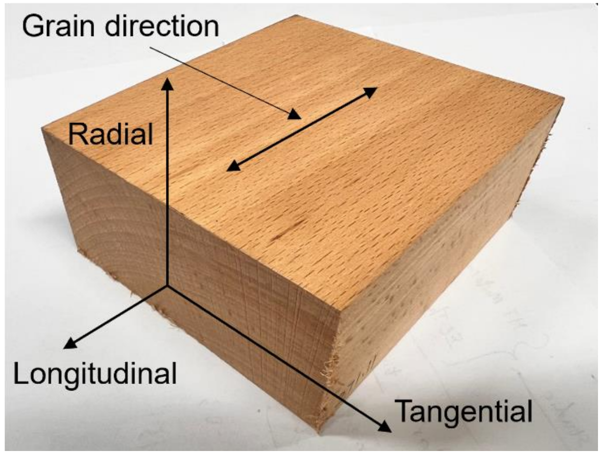
Localised fire model [7]:
Alpert ceiling jet model
EC1 localised fire model (Hesami model)



Natural fire model [8]:
Localised, travelling

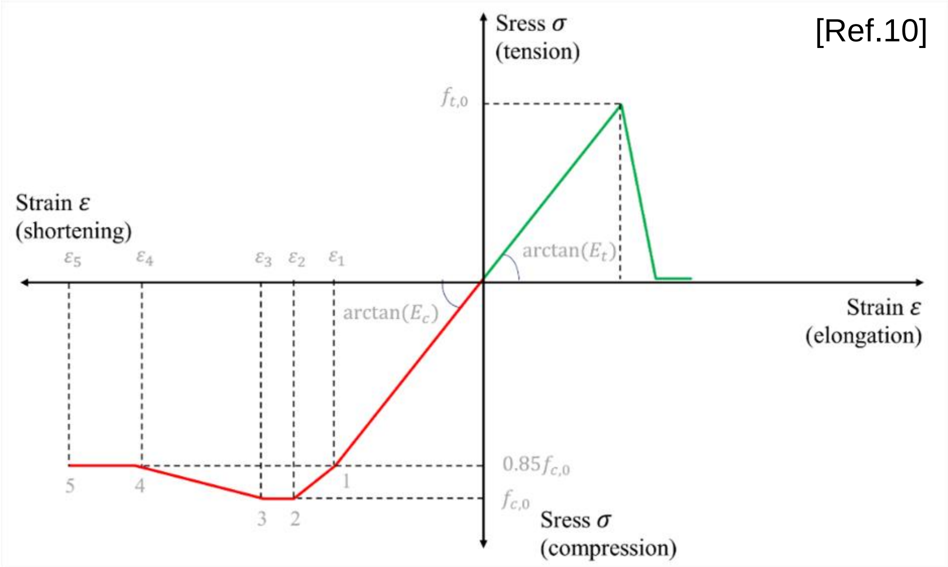
2.1 Constitutive model for timber





A constitutive model for timber

- Typical anisotropic material (Stress direction)
- L, R, T direction
- Elastic-plastic damage (Compressive zone)
- Brittle damage (Tensile zone)



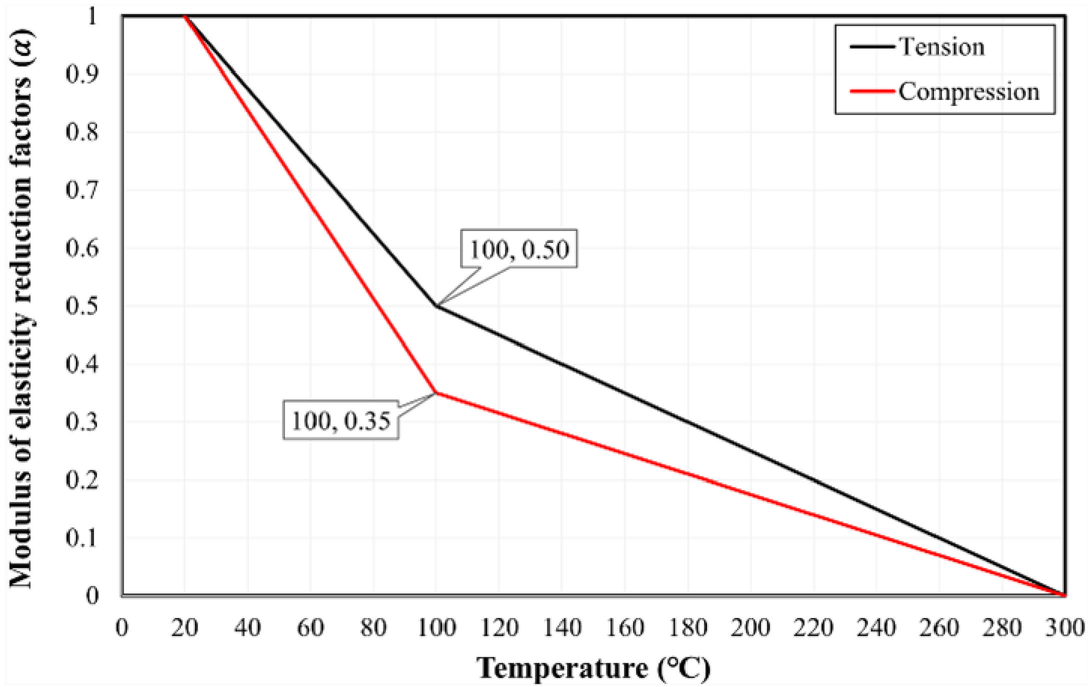
Node	Strain	Stress (MPa)
1	$\varepsilon_1 = \frac{0.85 \times f_{c,0}}{E_c}$	$\sigma_1 = 0.85 \times f_{c,0}$
2	$\varepsilon_2 = 0.925 \times \varepsilon_0$	$\sigma_2 = f_{c,0}$
3	$\varepsilon_3 = 1.075 \times \varepsilon_0$	$\sigma_3 = f_{c,0}$
4	$\varepsilon_4 = 1.700 \times \varepsilon_0$	$\sigma_4 = 0.85 \times f_{c,0}$
5	$\varepsilon_5 = 0.01$	$\sigma_5 = 0.85 \times f_{c,0}$

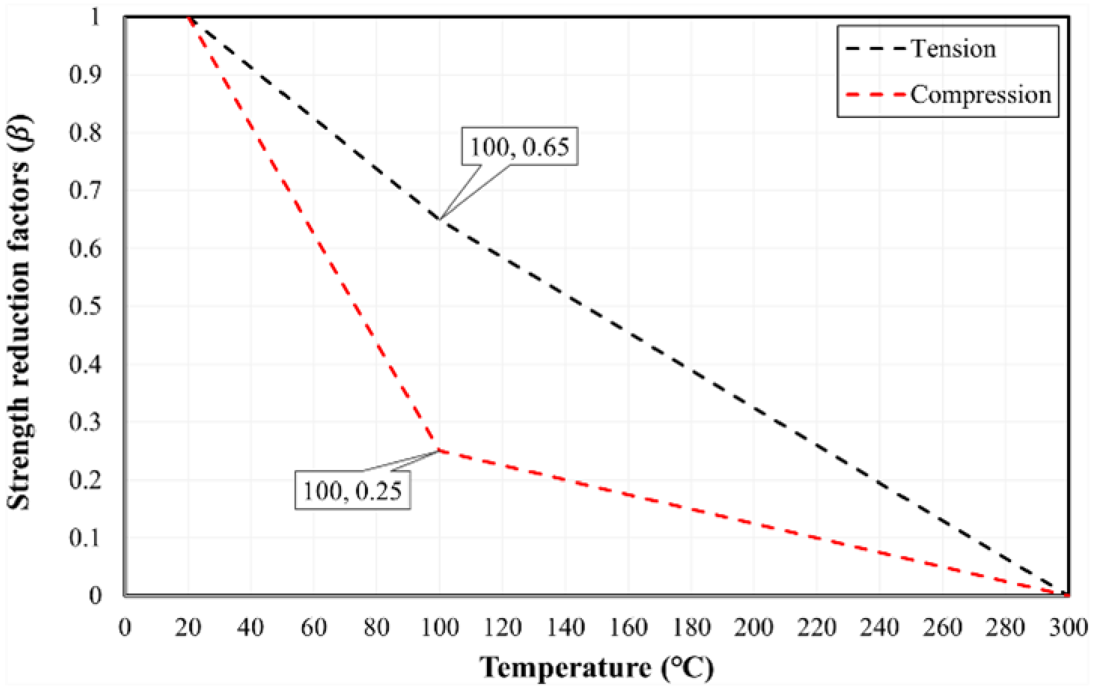
Constitutive model developed by Glos [11]

- Linearisation of the compressive zone (By Hartnack [12])
- Rapid decline of tensile stress within a small strain range (Considering computational convergence)

2.2 Mechanical properties of timber at elevated temperature

[Ref.10]





Eurocode 5 Annex B3

- Reduction factors
- Before drying and after charring
- Maximum temperature co-works with the heat transfer model to prevent backward state change of timber layers when temperature declines
- Limitations induced by the limited test data and the linear interpolation imposed

2. Development of thermo-mechanical model for timber members in fire

2.3 Zone-based thermal action for timber beams

Temperature data from heat transfer module

↓ Thermal action → Thermal-mechanical element

↓ BeamThermalAction3D (developed) → Timber beam and column with multiple sides of fire exposure

Heat transfer analysis on timber section

↓

Temperature data files
- 5 coordinate values along y and z, respectively
- 25 temperature values at the grid composed of coordinate positions

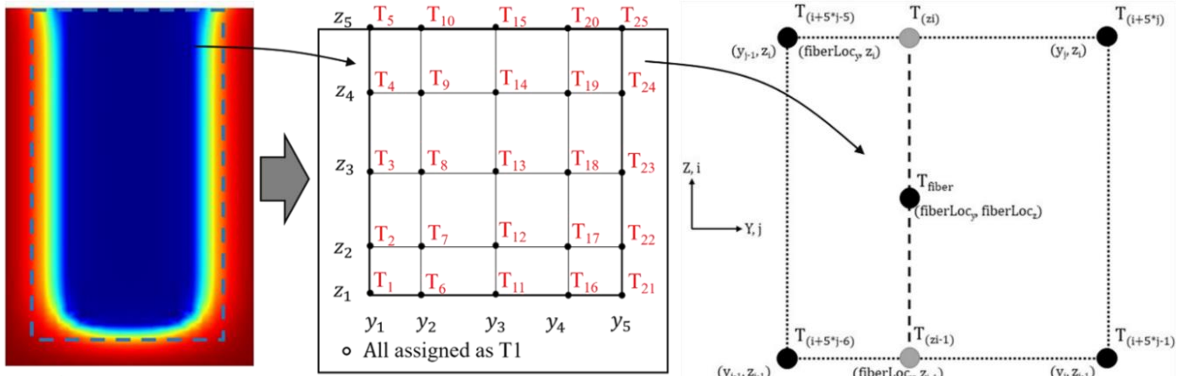
↓

Function (genInterpolation) will be automatically performed to determine the fibre temperature within each cell of the grid

$$
\begin{cases}
T_{zi-1} = T_{(i+5*j-6)} + \left(\dfrac{fiberLoc_y - y_{i-1}}{y_i - y_{i-1}}\right) \times \left(T_{(i+5*j-1)} - T_{(i+5*j-6)}\right) \\
T_{zi} = T_{(i+5*j-5)} + \left(\dfrac{fiberLoc_y - y_{i-1}}{y_i - y_{i-1}}\right) \times \left(T_{(i+5*j-5)} - T_{(i+5*j)}\right) \\
T_{fiber} = T_{zi-1} + \left(\dfrac{fiberLoc_z - z_{i-1}}{z_i - z_{i-1}}\right)\left(T_{zi} - T_{zi-1}\right)
\end{cases}
$$

It is interpolated first along the y-axis and then along the z-axis to calculate the temperature at the fibres

[Ref.10]



Section Temperature profile (from HT) (a)

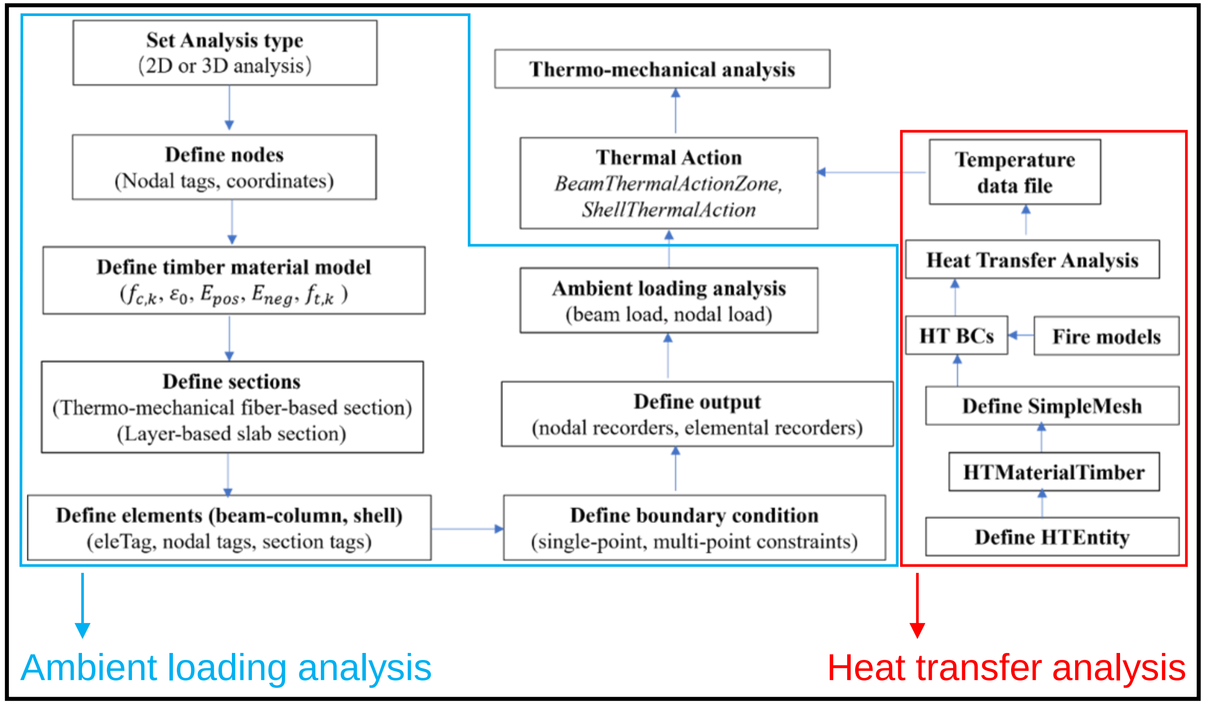
Adjustable zones (b)

Cell interpolation (c)

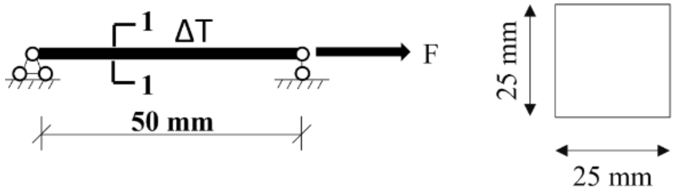
a) Temperature profile of timber beam with three-side fire exposure
b) Zone-based thermal action
c) Cell interpolation for timber fibre temperature

2.4 Modelling procedure in OpenSees for fire for timber members in fire [Ref.10]

Currently, the Tcl interpreter as a default choice is employed to interpret the input script to modelling procedures of OpenSees.

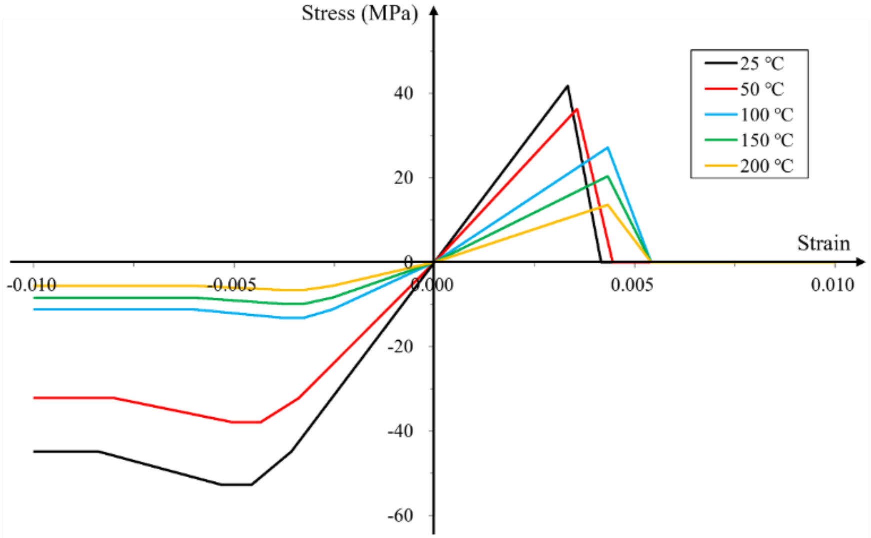


Thermo-mechanical analysis



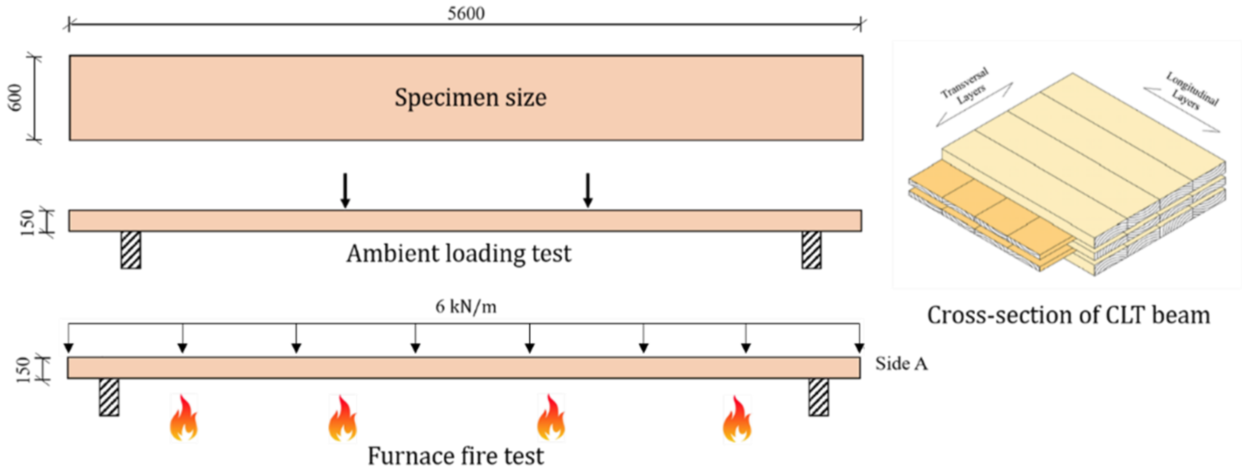
Finite element model

- ❑ Uniaxial tension and compression test
- ❑ Ambient loading and fixed temperature loading



Material degradation of timber fibers

Case 2 – Fire resistance of timber members exposed to fires



CLT panel tests [13]

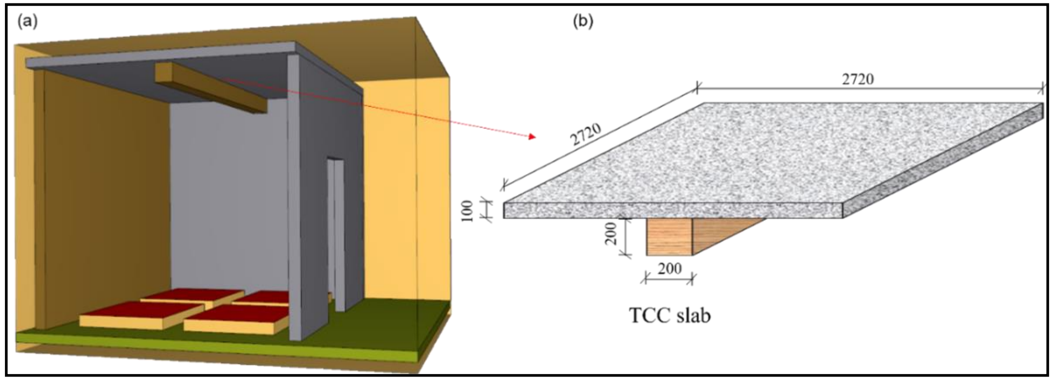
- **Size:** Cross-section of 600 mm × 150 mm
- **Moisture content:** 12%
- **Density:** 452 $\mathrm{kg/m^3}$

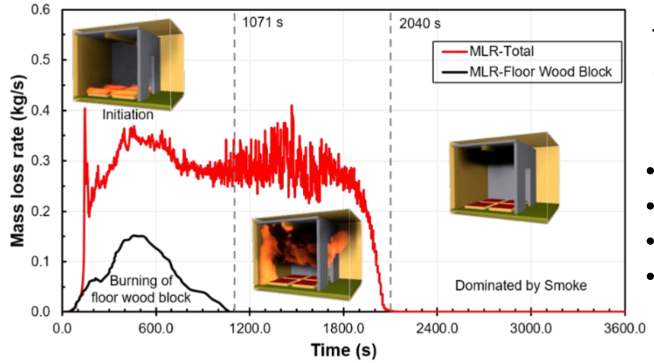
} Enough for heat transfer analysis

- **Layers:** Five layers (odd) and the thicknesses were symmetric, 42 mm (L), 19 mm (T), 28 mm (L), 19 mm (T), and 42 mm (L)
- **Loading method:** Two-point loading (uniformly distributed load of 6 kN/m)
- **Fire condition:** Standard fire furnace heating at the bottom
- **Layer Material:** Spruce (C24 strength grade)

C24 grade	Ultimate compressive strength (MPa)	epsc0	Elastic modulus under tension (MPa)	Elastic modulus under compression (MPa)	Ultimate tensile strength (MPa)
L layer	52.74	$4.93e^{-3}$	12564	12564	41.80
T layer	5.30	$3.50e^{-2}$	120	120	4.20

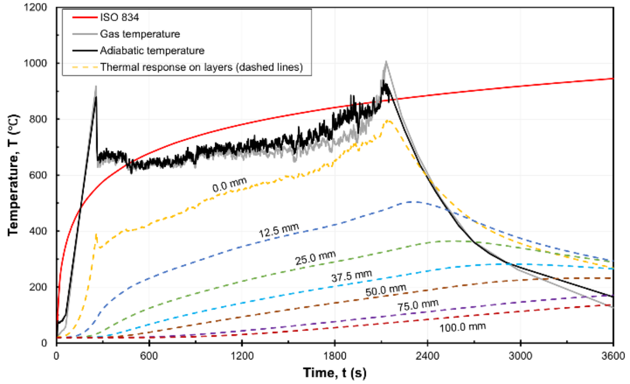
Case 3 – The composite member (TCC) in realistic fire scenarios

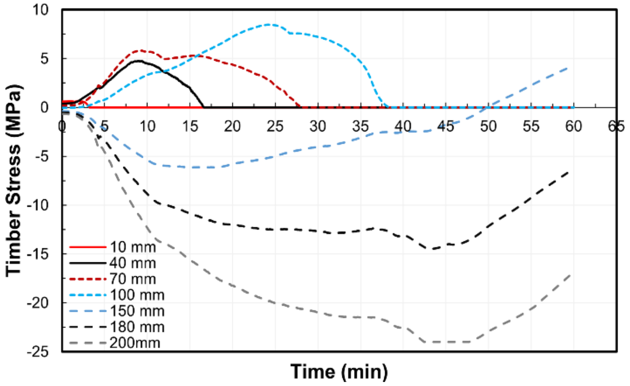


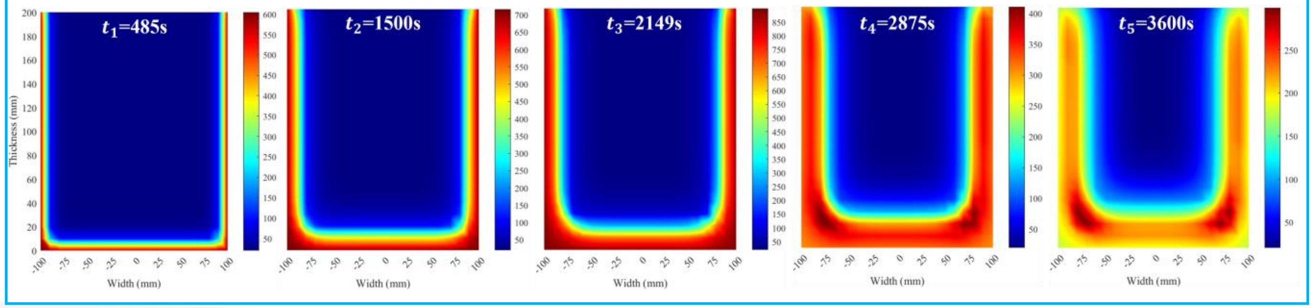


The fire development is simulated using a model in Fire Dynamics Simulator (FDS).

- Inspired by the experiments of Hadden et al. [14]
- Wood cribs were replaced by burners
- Definition of MLR follows the Alpha test data
- Simply-supported slab assembly







The time-variant gas-phase temperatures and adiabatic temperatures (Main task: **Non standard fire development history**)

HT analysis
Concrete slab (One-side fire exposure), Timber beam (Three-side fire exposure)

Thermo-mechanical analysis
Under uniformly distributed load (UDL)

Thermo-mechanical responses

- Central deflection of the slab under different UDL
- Timber stresses at different locations of midspan section

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Thanks for your listening

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