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**SIMULATION OF TIMBER MATERIAL AND
STRUCTURAL MEMBERS IN FIRES WITH
OPENSEES FRAMEWORK**

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PhD

The Hong Kong Polytechnic University

2025

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**Simulation of Timber Material and Structural Members in
Fires with OpenSees Framework**

Cheng Chen

A thesis submitted in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

April 2025

CERTIFICATE OF ORIGINALITY

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Abstract

Engineered timber offers significant sustainability benefits and architectural advantages, but its combustibility can lead to rapid fire spread in large open-plan compartments, limiting its wider adoption. This thesis addresses this challenge by developing advanced simulation tools and design strategies to improve the fire performance of timber structural systems. The related work is presented in 7 chapters, with brief introductions to each chapter as follows:

Chapter 1 introduces the research background, motivation, and the workflow of this thesis.

Chapter 2 developed an enhanced heat transfer model for timber within the open-source OpenSees framework, incorporating temperature-dependent thermal properties and the heat generated by timber combustion. Validated against experimental data, this model accurately predicts temperature evolution in timber sections exposed to realistic (non-standard) fire scenarios.

Chapter 3 established a coupled fire-structure analysis framework for modelling structural timber members subjected to different fire-exposure conditions with appropriate thermal actions based on the developed heat transfer model, demonstrating good agreement against selected fire test results. In this approach, thermal outputs from CFD compartment fire simulations were applied to OpenSees models of a timber-concrete composite slab for preliminary studies. This integrated simulation demonstrated the platform's capability to predict structural responses under realistic fire conditions.

Chapter 4 proposed a novel timber-insulation mixed ceiling design to mitigate fast-growing fire in a large compartment with timber ceiling. High-fidelity CFD simulations calibrated against large-scale fire tests showed that alternating non-combustible insulation and timber strips in lower layer of the ceiling can mitigate slow flame spread, achieving a similar fire behavior to compartment with non-combustible within 30 min.

Chapter 5 considered more realistic compartment and fuel configurations, which includes ceiling beam effect, non-uniform fuel load distribution, window height, and more challenging ignition locations. Results indicate that conventional uniform fuel distribution may underestimate fire risks. Beam arrangements influence local fire development, while compartment opening heights affect overall fire development. These factors must be considered in performance-based fire safety design. Optimized mixed ceilings can handle more challenging fire scenarios.

Chapter 6 further developed an orthotropic damage-plasticity material model for two-way timber slabs and implemented in OpenSees to simulate load-bearing slab behavior in fire. Validation against a full-scale two-way CLT slab fire test showed that this model reliably captures structural deflections and failure. Applying the model to composite slabs with the mixed ceiling design demonstrated enhanced fire resistance (exhibiting only 40% to 70% of the deflection) relative to conventional full-timber slabs.

Chapter 7 summarizes the overall outcomes from the works of this thesis, followed by description of further research directions to be addressed for achieving fire safe timber-integrated slabs.

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Nomenclature

Symbols		CLT	Cross-laminated timber
C_e	Thermal capacity matrix	EBTEA	Energy-based time-equivalent approach
C_p	Specific heat (kJ/kg-K)	EC 5	Eurocode 5
E	Modulus of elasticity	FDS	Fire dynamics simulator
$E_{neg,T}$	Temperature-related modulus of compression elasticity	FEM	Finite element method
$E_{Pos,T}$	Temperature-related modulus of tensile elasticity	FP	Full-protection
f	Stress (MPa)	FT	Full-timber
$f_{c,0}$	Ultimate compressive stress	FTC	Full timber composite
$f_{c,T}$	Temperature-related compressive strength	GLT	Glue-laminated timber
$f_{c,end}$	Asymptotic compressive stresses	HRR	Heat release rate
$f_{t,0}$	Ultimate tensile stress	HRRPUA	Heat release rate per unit area
$f_{t,T}$	Temperature-related tensile strength	HT	Heat transfer
G_d	Dry weight	H-TRIS	Heat-transfer rate inducing system
G_0	Initial weight	L	Longitudinal layers of CLT
ΔH	Heat of reaction (MJ/kg)	LVL	Laminated veneer lumber
k	Conductivity (W/m-K)	MLR	Mass loss rate
K_e	Conductive matrix	MTC	Mixed timber composite
n	Fire step number in FEM	NSF	Non-standard fire
P_{tag}	Phase tag	OPS	OpenSees
Q_e	Heat received at element surface or internally generated	OPS_Shell	OpenSees shell model
$\dot{q}''$	Heat flux (kW/m ²)	OPS_Beam	OpenSees beam model
q_S	External heat flux vector	PF	Parametric fire
q_V	Volume heat	RCSM	Reduced cross-section method
S	Surface	SF	Standard fire
T	Temperature (K)	T	Transversal layers of CLT
$\dot{T}$	Temperature increment vector	TCC	Timber-concrete composite
ΔT	Temperature difference (K)	TM	Thermal-mechanical
V	Volume	UDL	Uniformly distributed load
ε	Strain	ZSL	Zero strength layer
Greeks			
Abbreviation		ρ	density (kg/m ³)
1D	One dimension	Subscripts	
2D	Two dimensions	c	Compressive behaviour
AM	AREA_MULTIPLIER	t	Tensile behaviour
BC	Boundary condition	s	Surface
BD	BULK_DENSITY	v	Volume
CFD	Computational fluid dynamics	i	Trial phase tag in FEM

Publications

Refereed Journal Articles

1. C. Chen, L. Jiang*, M S. McLaggan, S. Wang, A. Usmani (2024). *Modelling heat transfer of timber sections subjected to non-standard fire actions*. **Fire Technology** (2nd Revision Submitted)
2. C. Chen, L. Jiang*, J. Qiu, M. A. Orabi, W. S. Chan, and A. Usmani (2023). *OpenSees development for modelling timber structural members subjected to realistic fire impact*. **Fire and Materials**, vol. 47, no. 4, pp. 461–478, 2023, doi: [10.1002/fam.3115](https://doi.org/10.1002/fam.3115)
3. C. Chen, F. Wiesner, T. Chu, A. Usmani, L. Jiang* (2024). *A conceptual design of timber-insulation mixed slab surface to mitigate large open-plan compartment fire development*. **Journal of Building Engineering**, doi: <https://doi.org/10.1016/j.jobbe.2025.112297>.
4. C. Chen, F. Wiesner, T. Chu, Y. Nie, A. Usmani, L. Jiang* (2025). *Applying timber-insulation mixed ceiling strategy in CFD simulation of large open-plan compartment with non-uniform fuel load*. **Fire Safety Journal** (1st Revision submitted)
5. C. Chen, J. Zhao, J. Qiu, A. Usmani, L. Jiang* (2025). *Numerical simulation of timber composite slabs in fires using OpenSees for fire*. (Pending submission to Engineering Structures)

Conference Presentations

1. L. Jiang*, C. Chen, A. Usmani. *A conceptual timber-steel composite section using char layer as insulation to protect steel*, in **World Conference on Timber Engineering** (WCTE 2021), Santiago, Chile, 9-12 August 2021.
2. J. Wang, C. Chen, T. Chu, L. Jiang*, V. Nimje, T. Yarlagadda, A. Usmani. *Experimental study and OpenSees modelling for thermal response of 3D-Printed concrete exposed to fires*, in **the 4th International Conference on 3D Construction Printing** (3DcP 2023), Singapore, 19-21 Jul 2023.
3. C. Chen, L. Jiang*, T. Chu, A. Usmani, *Preliminary study of a timber-insulation mixed surface to mitigate fire spread in compartments with timber ceiling*, in **Applications of Structural Fire Engineering** (ASFE 2024), Nanning, China, 25-27 Feb 2024.
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5. 陳誠, 趙敬賢, 仇錦, Asif Usmani, 江黎明*. 基於 OpenSees for fire 的木材複合樓板火災數值模擬, 於第二十五屆全國現代結構工程學術研討會, 常州, 中國, 2025 年 7 月 18 日至 20 日。

Post Presentations

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List of Papers not included in the Thesis

1. T, Chu, W, Zeng, G, Wang, C. Chen, G, Zhang, D, Yuan, ... L, Jiang*. (2025). *Explain why active opening of windows can mitigate fire spread in modern building compartments*. **Journal of Building Engineering**, 99, 111615-. <https://doi.org/10.1016/j.jobbe.2024.111615>
2. J, Wang, S, Li, J, Qiu, C. Chen, T, Chu, Y, Tian, ... L, Jiang*. (2025). *Experimental investigation on thermal performance of 3D printed concrete elements subjected to fire*. **Fire and Materials** (Accepted).
3. Y. Nie, C. Chen, A. Usmani, L. Jiang*. (2025). *Exploration of design variables for mixed timber-insulation ceiling following a localized fire model approach*. **Fire Safety Journal** (Submitted).
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Chapter 1: Introduction

Timber as a structural material has been increasingly popular in modern constructions due to its sustainability, aesthetics, and good manufacturability. However, the use of timber owing to its combustibility poses a high risk of rapid fire spread and large fire potentially leading to structural collapses. Over the past two decades, many timber building fires, as shown in Fig. 1.1, have demonstrated the large scope of fires after unstoppable fire spread, which have also resulted in significant economic losses, infrastructure damage, and loss of life. To mitigate these risks, specialized fire safety design for timber structures is essential. This requires extensive experimental studies and advanced numerical modelling techniques. Such studies offer valuable insights into the thermal and thermomechanical behavior of timber materials, the fire dynamics within timber compartments, and the overall structural integrity during a fire. As timber buildings continue to rise, it is crucial to develop a comprehensive fire safety framework to address these challenges and ensure safe evacuation. This thesis aims to advance fire safety in modern timber structures, particularly large open timber compartments, by developing a more effective thermomechanical response prediction model and a performance-based fire safety design strategy. Through a deeper understanding of fire dynamics and the implementation of appropriate safety measures, this work seeks to ensure that future timber structures can meet the necessary fire safety performance standards.



Fig. 1.1. Fire accidents in timber buildings: (a) Colindale Fire in NW London, UK, 2006 [1]; (b) Metropolitan Apartment Fire in Raleigh, USA, 2017 [2]; (c) Worcester Park Fire in London, UK, 2019 [3]; (d) Wood Roof Fire of the Notre Dame Cathedral, France, 2019 [4]; (e) Motorcycle Museum Fire in Tyrol, Austria, 2021 [5]; (f) Construction Site Fire in West Vancouver, Canada, 2024 [6].

1.1 Background and motivation

Timber has been increasingly adopted in mid- and high-rise construction owing to its sustainability and aesthetic appeal, contributing significantly to global carbon neutrality initiatives. However, timber's inherent combustibility introduces significant fire safety challenges. Fires involving timber structures often feature prolonged combustion, high heat release rates (HRR), and rapid flame propagation compared to non-combustible buildings [7]. Recent severe fires involving large-scale timber structures have highlighted these risks, causing significant economic losses and casualties, thus necessitating reassessment and improvements in fire safety design methods for timber buildings. To ensure safe timber utilization, it is essential to develop an integrated fire safety system combining experimental studies and numerical simulations to evaluate timber's thermal and structural behaviours during realistic fire scenarios. This is particularly crucial for large open-plan timber compartments, where complex fire dynamics invalidate traditional assumptions. Hence, this research focuses on three key issues: (1) limitations of existing heat transfer models (e.g., Eurocode 5) under realistic fire scenarios; (2) unusual fire dynamics challenges and fire safety strategies for modern open-plan compartments; and (3) the inherent limitations of conventional fire resistance testing and the necessity for advanced numerical modelling approaches.

1.1.1 Limitations of current heat transfer models and the need for improved models under real fire

As shown in [Fig. 1.2](#), current fire design for timber structures largely follows prescriptive guidelines, notably Eurocode 5 (EC5) [8], which recommends the Reduced Cross-Section Method (RCSM) for calculating residual load-bearing capacity under standard fire exposure [9]. However, the applicability of EC 5 methods to modern engineered timber products, particularly cross-laminated timber (CLT), remains questionable [10]. Wiesner et al. highlighted that EC 5 methods originally developed for glulam members are frequently employed for CLT without adequate validation [10]. Furthermore, the RCSM assumes a Zero Strength Layer (ZSL) depth of 7 mm, derived from historical bending tests on glulam beams [11], a value whose general applicability has been recently questioned for different structural configurations, load conditions, and heating scenarios [12-14].

Moreover, most studies and standards focus on standardized heating curves, such as ISO 834 [15], neglecting realistic fires characterized by heating and cooling phases [16-18]. Real fire scenarios often feature post-peak temperature decay, where timber may extinguish externally but internal temperatures continue rising due to heat penetration, increasing the risk of structural collapse during cooling phases. Gernay's finite element modelling study demonstrated timber columns remain vulnerable post-cooling due to delayed heating and mechanical degradation [19]. Similarly, Wiesner et al. observed prolonged heat penetration and sustained reduction in bearing capacity even after flame extinction [20]. Kinjo's [21] study on GLT beams and Hirashima's [22] investigation of GLT columns during the cooling phase also highlighted that after the heating phase ended, the temperature within the cross-section continued to rise gradually,

reaching nearly 100°C at the centroid, resulting in delayed failure. Such phenomena are inadequately represented by existing EC5-type models [23-25] and energy-based time equivalent models [26, 27], which neglect timber's internal combustion heat generation, a critical deletion for accurate thermal response predictions. Thus, there is an urgent demand to develop advanced heat transfer models capable of accurately predicting timber's thermal response under realistic fire scenarios, incorporating complex temperature-dependent thermal properties [23, 24, 28] and internal heat generation due to combustion processes.

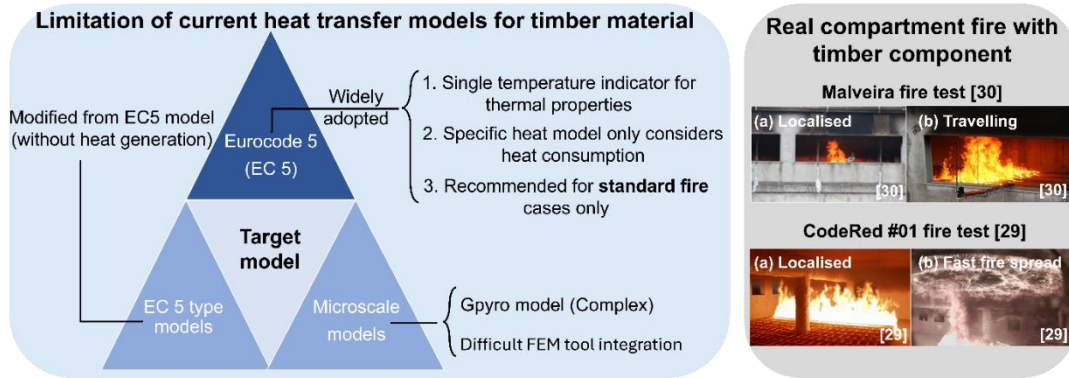


Fig. 1.2. Targeted heat transfer (HT) model with enhanced functionality based on the existing HT models for timber materials under fire and real fire behavior in modern compartments with timber components [29, 30].

1.1.2 Fire dynamics in large open-plan timber compartments: new challenges and safety design

Timber's combustibility makes it an additional fuel source in fires, affecting compartment fire dynamics by accelerating fire spread, increasing external flames, and prolonging fire duration. Concerns have grown regarding the potential fire hazards posed by timber elements in such buildings. For this reason, over the past few decades, researchers around the world have conducted a substantial number of fire tests at various scales: micro-scale tests using cone calorimeters for timber materials [31, 32], medium-scale furnace tests for timber structural components [33, 34], and full-scale compartment fire tests [7, 35, 36], as shown in Fig. 1.3. These tests, mostly conducted in smaller, ventilation-controlled compartments (typically 20 m² to 40 m²), show that exposed timber accelerates fire growth and increases heat release rates. However, due to the recent advances in engineered timber have facilitated widespread use in large open-plan spaces, conventional fire dynamics and fire safety designs derived from smaller compartments may not be applicable [37-40]. Therefore, investigating fire dynamics in modern compartments is essential for systematically developing appropriate fire safety methods. Studies have shown that large open-plan compartments with large openings and sizes are more prone to travelling fires [30, 39, 40]. Experimental tests, including the Edinburgh travelling fire test [41], the x-ONE fire test [42], and the Malveira fire test [30], all observed travelling fire [39, 40] characterized by non-uniform temperature distribution and varied burning behavior in the near and far field, which significantly differ from fire dynamics in conventional small compartments. However, these tests were largely conducted in non-combustible compartments.

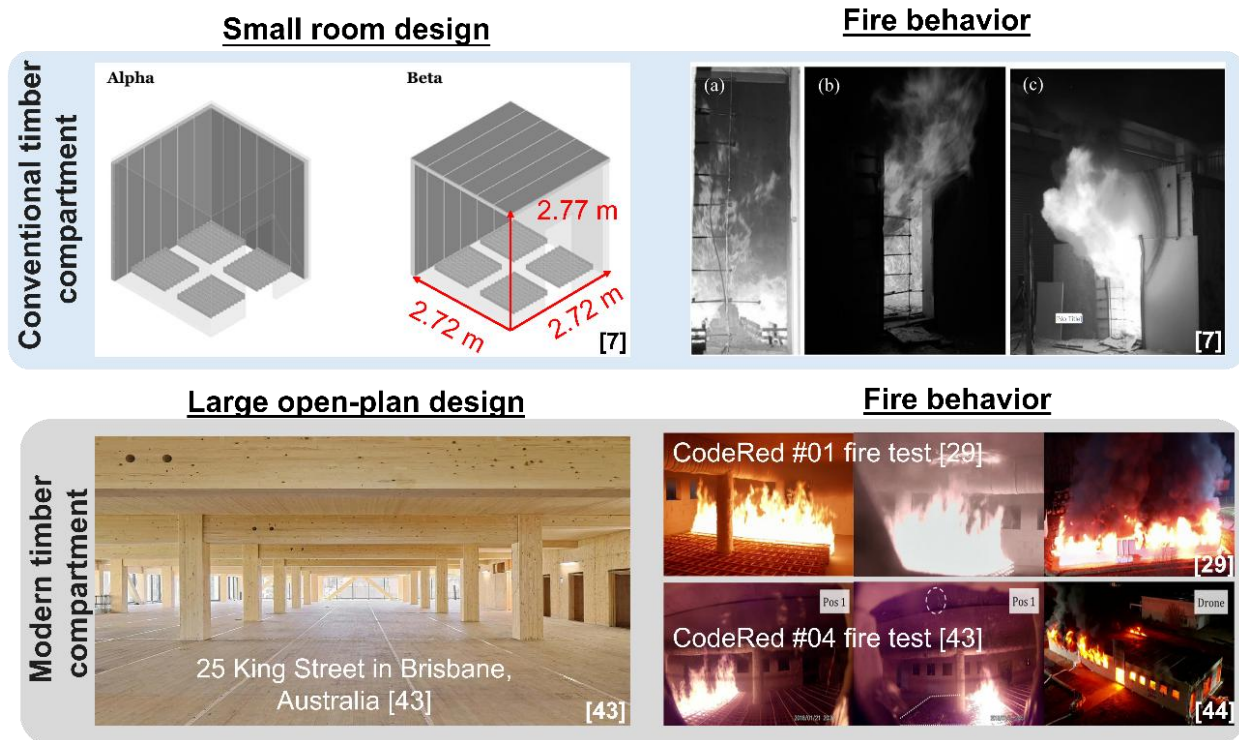


Fig. 1.3. Summary of the differences between conventional and modern large open timber compartment forms and potential rapid fire spread risks [7, 29, 43, 44].

Oriented towards modern compartment forms and the flammability of timber material, fearful phenomena were observed in fire experiments in large open compartments with continuous timber ceilings. For example, the CodeRed#01 test by Kotsovinos et al. demonstrated rapid fire spread and fire engulfing whole compartments within five minutes after CLT ceiling ignition in a 352 m² compartment [29]. Even partial encapsulation (CodeRed#04) merely delayed ignition without significantly mitigating spread rates [44]. Andreas et al.'s FRIC-01 test in a 95 m² compartment observed altered fire dynamics upon ceiling ignition, with better ventilation reducing rapid fire spread and preventing instantaneous flashover [45]. Non-uniform fuel distributions, reflecting realistic scenarios, were found by Nan et al. to significantly exacerbate localized high-temperature zones, indicating traditional uniform-fuel assumptions underestimate fire risks [46]. Therefore, traditional compartment fire design inadequately addresses the fire hazards in modern large open timber compartments, necessitating novel strategies that balance sustainability and fire safety. There is also a need to explore the design of relevant measures for integration with the initial compartmentalized building design, such as combustible layouts and ventilation conditions associated with openings.

1.1.3 Limitations of conventional fire resistance testing and the need for numerical simulation tools

Conventional fire resistance testing methods (e.g., large-scale furnace tests) face inherent limitations due to cost, environmental factors, and size constraints, inadequately representing realistic compartment fire scenarios. Repeated large-scale physical experiments under varied scenarios are economically and

logistically impractical. Hence, advanced numerical modelling has become indispensable, enabling controlled, repeated, and comprehensive fire simulations and response analyses.

As shown in Fig. 1.4, the OpenSees platform, initially developed for earthquake engineering [47], has been extended for structural fire analysis, including heat transfer and structural response modules [48, 49]. Recent developments incorporate layered heat transfer models accounting for moisture evaporation, pyrolysis, charring transitions, and combustion heat effects [50]. Thermomechanical constitutive models reflecting EC5 material degradation criteria were validated against standard and realistic fire tests on CLT and glulam beams [50, 51]. To overcome limitations in simulating two-way load-bearing slabs, orthotropic plastic-damage constitutive models were introduced, capturing anisotropic mechanical degradation, tensile/shear brittle failures, and compressive softening behaviors [51]. Coupling CFD fire dynamics and OpenSees structural simulations enables a realistic assessment of structural systems under fire. These numerical advancements offer robust alternatives to costly physical experiments, promoting safer timber utilization and enabling sophisticated performance-based fire safety designs.

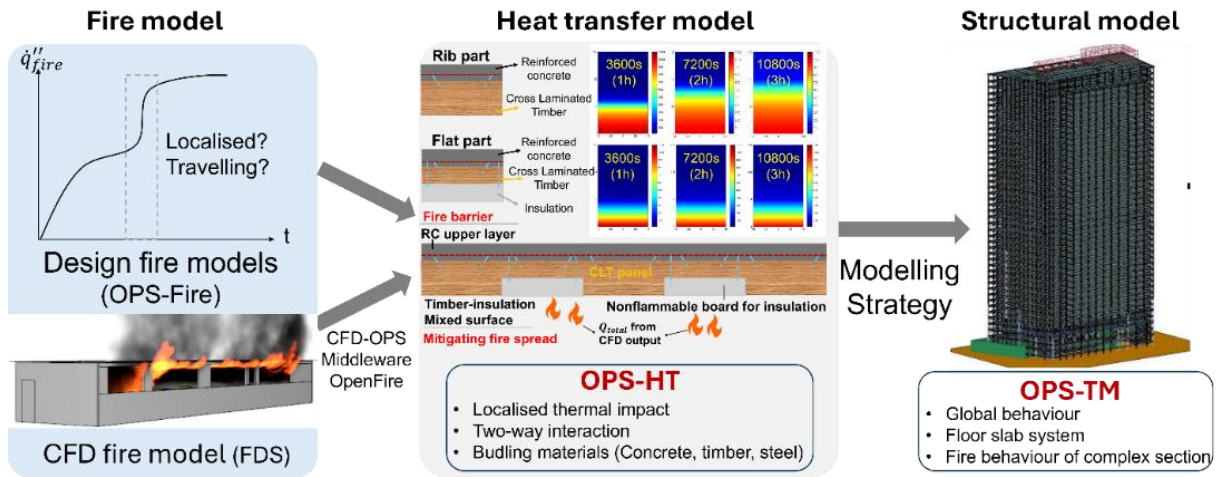


Fig. 1.4. Modelling framework for timber structural in fires based on the numerical simulation platform integrating the advanced and open-source OpenSees for fire and CFD.

1.2 Aims and objectives

In response to the above challenges, this thesis aims to develop modelling for simulating fire response of timber structural members in the context of modern buildings and to explore innovative design strategies to improve the fire safety performance of timber-integrated buildings. Therefore, the main research questions are raised prior to this thesis:

- (1) How to simulate the thermomechanical response of timber structures under fire by using the open-source finite element framework OpenSees for fire?
- (2) How to balance the use of timber materials for sustainability and fire safety in modern large open-plan compartment design?

To explore the answers to the above two questions, this thesis is targeting the following objectives:

- To develop a heat-transfer model for timber under non-standard (realistic) fire exposures within the OpenSees for fire framework, incorporating temperature-dependent material degradation (drying, charring, and ashing) and a heat generation model to capture the effect of timber combustion.
- To integrate the heat transfer model with structural analysis in OpenSees for fire to establish a coupled thermo-mechanical simulation capability for timber components under fire. This includes simulating typical fire scenarios, for example, one-sided heating of timber slabs and three-sided heating of timber beams, and validating the predicted temperatures, charring depths, and structural responses against full-scale fire test results.
- To extend the modelling framework to more realistic timber systems by developing the timber material models for two-way load-bearing timber slabs exposed to fire. This involves implementing a material model capturing high-temperature damage and damage evolution of timber material and incorporating realistic fire inputs as the boundary condition from CFD fire simulations. Through this extension, the thesis evaluates the fire performance of timber-concrete composite slabs and similar floor systems, laying the groundwork for performance-based fire design of modern and future timber-integrated buildings.
- To explore novel design strategies that mitigates rapid flame spread in large open-plan compartments, which comprises a timber-insulation mixed ceiling design with timber strips and insulation strips. The performance of this design will be examined through CFD simulations and compared against fire tests of large compartments with/without timber ceiling.
- To investigate the influence of key design factors on compartment fire dynamics to inform balanced design guidelines. Using parametric studies of large timber-integrated compartments (employing the mixed ceiling concept), examine how variations in fuel load distribution (uniform vs. non-uniform), structural layout (e.g. ceiling beam arrangements), and ventilation conditions (window opening heights) affect fire development.

Each set of objectives above corresponds to a group of research tasks in the thesis. Together, these objectives provide a structured pathway from fundamental modelling improvements to practical fire-safety design solutions for timber in large compartments, aligning with the overall aim of enhancing fire-safe, sustainable use of mass timber in construction.

1.3 Structure of the thesis

This thesis is a compilation of five publications prepared during the PhD study, providing ideas and measures for promoting fire numerical simulation and fire safety design for timber through the use of the

OpenSees for fire open-source platform and CFD simulation tools in conjunction with experimental studies. The corresponding research ranges from developing predictive models for the thermal response of timber sections and the thermomechanical behavior of timber components exposed to fires to studying fire dynamics in large open compartments equipped with timber surfaces, along with corresponding fire safety design recommendations.

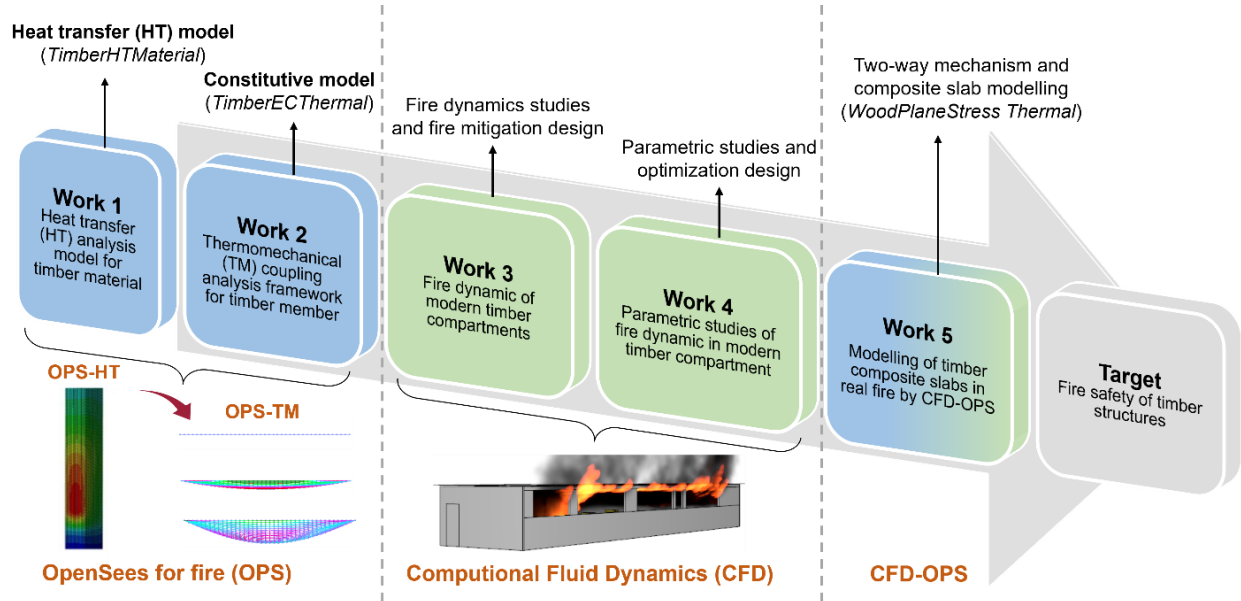


Fig. 1.5. A technical workflow for the overall research framework.

To further clarify the overall research framework and workflow, a technical roadmap (Fig. 1.5) has been incorporated to visually summarize the interconnection among the five major research works. The roadmap demonstrates that this research is structured into three progressive and interrelated parts:

- Part I (OpenSees for fire platform): development of a heat-transfer model and constitutive model for timber material (Work 1), and a thermomechanical coupling framework (Work 2) for analysing structural timber members, enabling quantitative prediction of temperature evolution and deformation responses under fire exposure.
- Part II (CFD fire-dynamic studies): investigation of the fire behaviour of modern large timber compartments using validated CFD fire model. The mechanisms governing rapid flame spread and fire growth are analysed, and a mixed-ceiling mitigation strategy is proposed (Work 3), followed by parametric studies exploring mitigation measures and design optimization (Work 4).
- Part III (CFD-OpenSees coupling): extension of the developed modelling capability to two-way load-bearing components, integrating realistic fire actions obtained from CFD into OpenSees for fire to simulate the thermomechanical behaviour of composite timber slabs under real-fire actions (Work 5).

Collectively, these parts form a continuous and coherent research pathway aimed at advancing performance-based fire-safety design methods and enhancing the safe, sustainable application of mass-timber structures in modern buildings. The details of each specific work are as follows:

Chapter 2 (work 1) addresses the challenge of fire safety in timber buildings, highlighting the inadequacies of Eurocode 5 for non-standard fire scenarios. It introduces a new heat transfer model for timber exposed to real fire conditions, incorporating temperature-dependent thermal properties and combustion effects. Implemented in OpenSees for fire platform, the model was validated against tests and demonstrated accurate predictions of temperature evolution within timber sections under non-standard fires.

Chapter 3 (work 2) focuses on advancing modelling for structural timber components by applying the developed heat-transfer and thermo-mechanical models within OpenSees for fire, capable of simulating responses of timber beams and slabs under different fire exposures. It also demonstrates a coupled CFD-OpenSees analysis for a timber-concrete composite slab, showcasing the potential of numerical simulation in advancing fire-modelling frameworks for timber structures.

Chapter 4 (work 3) explores fire risks in timber buildings, proposing a timber-insulation mixed ceiling design aimed at mitigating rapid flame spread. Using validated full-scale CFD fire models of the Malveira fire test, three different ceiling configurations including full-timber ceilings, mixed ceilings, and non-combustible ceilings were evaluated. The results showed that the mixed ceiling design could mitigate fire spread in large open compartments, promoting the safe application of mass timber in modern architecture.

Chapter 5 (work 4) further investigates the development of corresponding fire dynamics in large open compartments equipped with the aforementioned mixed ceiling under other configuration factors, including structural beam arrangements, more realistic fuel load distributions, and compartment opening heights. This aims to provide safety design guidance for modern large-scale timber compartments.

Chapter 6 (work 5) outlines the advancements in modelling two-way load-bearing timber slabs exposed to fire using the OpenSees for fire platform. It focuses on the development of a plastic damage model that accounts for the brittle fracturing in tension and shear and nonlinear softening in compression of timber under fire exposure. This model is integrated into shell elements, allowing for simulations of two-way load-bearing timber slabs under non-standard fire conditions. The findings demonstrate that the model can better predict the deflection and failure of timber slabs, while also showcasing the fire resilience of composite slabs with timber-insulation surfaces.

Lastly, **Chapter 7** summarizes the key findings of the thesis and outlines potential research directions for future research.

Chapter 2: Modelling Heat Transfer of Timber Sections Subjected to Non-standard Fire Actions

Summary

To enable realistic fire performance assessments of timber structures beyond the constraints of standard fire curves, Chapter 2 develops a heat transfer model for timber sections subjected to non-standard fire exposures. Recognizing the limitations of Eurocode 5 (EC5) and related models, particularly in their inability to simulate combustion-induced heat generation and the irreversible nature of char formation, the proposed model incorporates temperature-dependent thermal properties and a heat generation mechanism based on combustion effects. Implemented within the OpenSees for fire platform, the model uses a state-tagging method to track material phase transitions (e.g., dehydration, pyrolysis, charring) and updates thermal properties based on maximum historical temperature. The model was validated against a series of experimental tests, including time-varying heat flux exposures using the H-TRIS system, showing strong agreement in predicting temperature evolution across different timber depths. This layer-based heat transfer model provides a foundation for subsequent thermomechanical simulations, offering improved accuracy in evaluating timber's fire resistance under realistic compartment fires, and serves as a critical first step in developing a comprehensive simulation framework for timber structures in fire, which is expanded upon in the following chapters.

This chapter is based on “C. Chen, L. Jiang*, M S. McLaggan, S. Wang, A. Usmani (2024). Modelling heat transfer of timber sections subjected to non-standard fire actions. **Fire Technology**, (Submitting revision).”

2.1 Introduction

Timber is widely used in building construction as non-structural and structural components. As a renewable construction material, it is a promising structural material to reduce the carbon footprint of modern urbanization while a decarbonized economy is pursued for the concern of climate change. To use timber as load-bearing components in structures, its performance at ambient conditions has been extensively investigated, such as tests on solid timber members subjected to combined axial force and bending moment [52], laminated lumber (LVL) members [53] and cross-laminated timber (CLT) panels under bending [54] and scrimber composite members subjected to axial compression [55]. However, the combustible nature of timber has been a long-existing barrier to the broader application in the construction industry, especially for multi-story buildings. Unlike conventional structural materials (i.e., concrete, steel, and masonry), timber sections can burn in a fire, and the resultant char layer can propagate from the surface to deeper layers within the section. Therefore, estimating the thermal response of the timber section is a critical step in the fire safety design of timber structures. The current modelling practice provided in Eurocode 5 (EC 5) [56] is only allowed to predict the thermal responses of timber sections in standard fire exposure [57, 58], which may be suitable in a prescriptive manner but not applicable to realistic fire scenarios with cooling phase [19] in building compartments especially for fires in large open-plan compartments [30, 44, 45]. For the latter fire scenarios, timber sections are certainly exposed to time-variant fire action and the heat generated from timber burning plays an important role.

When timber sections are exposed to fire, a series of physical changes and chemical reactions occur. The initial wood layer is dehydrated as the moisture evaporates at around 100 °C. After dehydration, the wood is subjected to pyrolysis, which routinely occurs as slow pyrolysis below 200 °C, steady pyrolysis up to 300 °C and rapid pyrolysis above 300 °C [24, 59]. The combustible gases are the products of pyrolysis, after which the wood layer turns to a char layer (index temperature of charring is usually given as 300 °C) [60, 61]. The changing phases of timber induce much complexity to the heat transfer estimation, while the thermal properties of timber vary with temperature [23, 24, 28]. Experimental studies on the thermal response of timber sections have been conducted primarily using furnace fire tests prescribed in standard fire curve or parametric fire curve or using fixed heat fluxes in a cone calorimeter. A series of timber panels (1000 or 325 mm× 225 mm× 95 mm) were tested by König and Walleij [25] to investigate one-dimensional charring through the 95 mm timber section, which provided well-equipped specimens monitoring temperature evolution at various depths of the timber section subjected to Standard fire (SF) and Parametric fires (PF). White and Tran [62] used the cone calorimeter with various fixed heat fluxes (HF tests) ranging from 15 to 50 kW/m² to test the charring rate of different types of timber: pine, redwood, oak, and basswood. The reported work measured the timber temperature evolution at various depths, which offers rigorous reference to the modelling of timber response to a moderate range of heat fluxes. Tests on six kinds of

Chinese softwood and hardwood were conducted by Wen et al. [63] using three different fixed heat fluxes (35, 50, 75 kW/m²). Alongside the temperature data, the char depth growth in each test has been estimated using the thermocouple measured data with respect to the 300 °C isotherm. The average char rate in standard fire tests was found to be close to 0.65 mm/min as a recommended estimation in EC 5 [56], whereas a slower growth of the char layer was observed in the parametric fire tests undergoing a decay period [25], which are beyond the capability of EC 5 recommended heat transfer model.

In EC 5, the thermal properties of timber (i.e., density, conductivity, and specific heat) are given as temperature-dependent models, which formulates a model to address heat conduction only in timber sections, without consideration of heat generation from timber burning. To adapt the EC 5 model to non-standard fire scenarios, Zhang et al. [26] proposed an energy-based time-equivalent approach (EBTEA) to define equivalent standard fire load from non-standard fire exposure. This method provided a compromising approach for parametric fire scenarios while the heat of timber combustion remained ignored. Furthermore, heat release from timber combustion has not been considered in heat transfer models of timber sections [64]. It is noted that the Gpyro model [65] incorporating micro-scale level models of complex chemical reactions and physical changes presented accurate simulation of timber sections in the fire. Due to the technical complexity of a Gpyro model, an engineering model for timber structural design against various non-standard fire scenarios remains absent. The model proposed by Hopkin adopting a ‘heat of hydration’ principle described an easy-to-use model to account for the heat of timber combustion [66] was one attempt, which provides an inspiring methodology of considering the combustion heat but the model requires more consideration in heat release and validation against more non-standard fire scenarios. Complementary to these, Floyd and Hodges [67] proposed a flux- and thickness-scaling method that converts cone-calorimeter data into an effective ‘reference heat flux’ for engineering-level pyrolysis prediction of wood, offering a practical, calibration-light alternative.

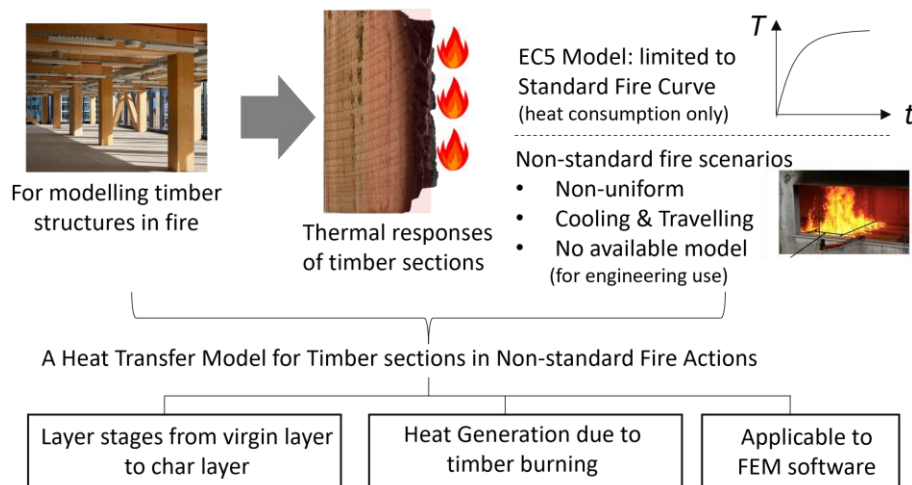


Fig. 2.1. The modelling needs for heat transfer model of timber sections exposed to non-standard fire.

In this chapter, modelling heat transfer of timber sections subjected to non-standard fire scenarios is explored and implemented in an open-source finite element modelling framework, which aims to provide an engineering-level approach to account for heat transfer under fire action covering a wide range of heat fluxes in realistic fire scenarios (Fig. 2.1). A combustion heat estimation model based on laboratory test results has been proposed to approximate the heat absorbed by the timber section. The proposed model has been implemented in OpenSees heat transfer module, and validation of this model has been conducted against experimental data. The effect of non-standard fire actions characterized using time-varying heat fluxes as the demonstration of more challenging scenario has been modelled and discussed, which has shown overall good performance in estimating the thermal responses of timber sections and a great potential in the implementation for fire safety design. As a part of open-source development, the source code and examples of this model have been made available at openseesforfire.github.io, which allows continuous improvement of the model in future application.

2.2 Background

2.2.1 Thermal response and layered states of timber exposed to fire

Timber surfaces exposed to fire are subject to the effect of external heat fluxes, resulting in the generation of flammable gas generation as pyrolysis products [24, 59]. As mentioned before, modelling the heat transfer of timber sections in fire should address the heat absorption as well as the heat generation [60, 61]. A timber layer routinely experiences different states namely virgin wood layer (virgin zone with the original moisture content), dried layer (dehydration zone), pyrolysis layer, char layer, and ash layer, as shown in Fig. 2.2a. When heated by an external fire, it is known that flames can sustain at the exposed surface of a timber section alongside the smouldering occurring in the charred layer underneath the flaming front. In case where the external heating is not intense enough to sustain the surface flaming, smouldering becomes the dominant mode of oxidative combustion and leads to further pyrolysis. Flaming and smouldering are both exothermic oxidation reactions emitting heat to the room environment, and the absorbed portion by timber itself can significantly affect the thermal responses of timber sections. As illustrated in Fig. 2.2b, the gross heat of timber combustion is mostly released to the surrounding environment ($\dot{q}_{comb_out}''$) in the form of flaming at the exposed surface of the timber and smouldering of the char layer. $\dot{q}_{comb_out}''$ is not absorbed by the timber section, whereas the absorbed portion ($\dot{q}_{comb_in}''$) contributes the heating to sustain the propagation of pyrolysis and charring.

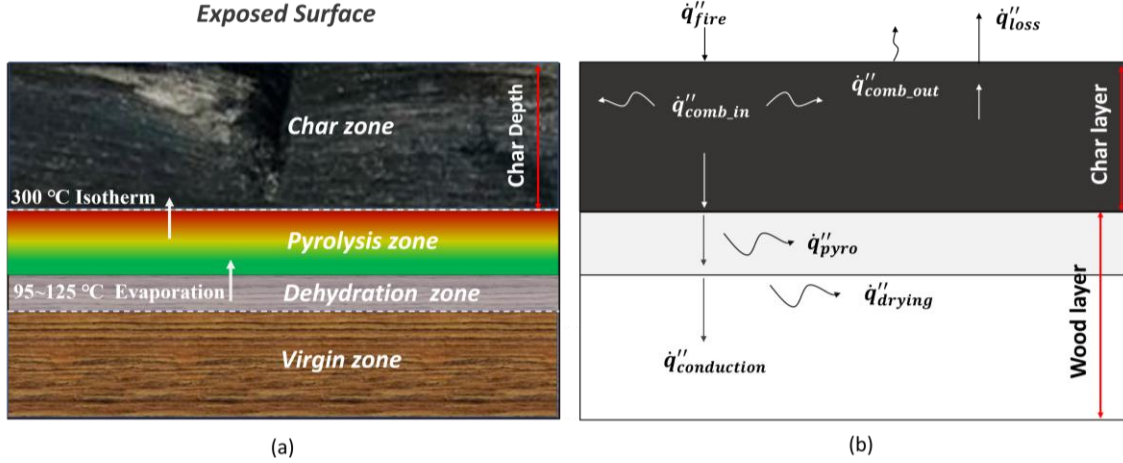


Fig. 2.2. Thermal response of timber exposed to fire: (a) Diagram of timber pyrolysis; (b) Heat transfer of timber section in fire.

To quantify $\dot{q}''_{comb_in}$, Section 2.3 introduces a comparative test using two heat flux gauges to measure the heat flux received from radiant panel and the heat flux received from both radiant panel and timber burning. The overall heat balance between the exposed surface and a deeper section of original wood may be expressed as:

$$\dot{q}''_{fire} - \dot{q}''_{loss} + \dot{q}''_{comb_in} = \dot{q}''_{pyro} + \dot{q}''_{conduction} + \dot{q}''_{drying} \quad (2.1)$$

Where $\dot{q}''_{fire}$ represents the external heat flux at the exposed surface induced by room fire, and $\dot{q}''_{loss}$ is the heat loss at the exposed surface. The net input heat fluxes on the left-hand side of Eq. 2.1 are to balance the endothermic heat consumption processes ($\dot{q}''_{drying}$, $\dot{q}''_{pyrolysis}$) and the heat conduction to the deeper section $\dot{q}''_{conduction}$. When the timber section is tested using furnaces of prescribed time-temperature curves, such as standard fire, this additional heating impact owing to timber combustion becomes negligible because the $\dot{q}''_{fire}$ is dominated by the designated furnace temperature. However, if considering the actual fire development in a modern compartment, the additional heat contributed by the burning timber (primarily $\dot{q}''_{comb_out}$) could cause the significant rise of $\dot{q}''_{fire}$ and change the fire behavior [30, 45, 68, 69]. Moreover, when the fire experiences a less intense period, the internally absorbed term, $\dot{q}''_{comb_in}$, becomes the major heat resource to sustain the ongoing propagation of pyrolysis and charring. If the external heat flux further reduces, self-extinguishment of timber can occur. Apparently, an EC5 type model is not able to address such heat balance as no heat generation ($\dot{q}''_{comb_in}$) is available. Therefore, in order to predict the thermal response of timber sections under non-standard fire actions, it is meaningful to establish a heat transfer model based on characteristic layer division and consider timber burning effects.

2.2.2 Existing models and the need for an engineering model for non-standard fires

Several models complement EC5 when fires are non-standard or include a decay phase as follows in Table 2.1, however, these models either need limited fire scenarios (EC5 type model), detailed kinetics (Gpyro model), target compartment energy balances (TiCHS model), simplified sources (Hopkin model), or limited testing scenarios and compartment boundary conditions consideration (Floyd & Hodges model). None directly deliver an engineering-oriented tool that both tracks layer states and incorporates heat generation from timber combustion under realistic fires with non-standard fire action.

Table 2.1. Existing heat transfer models for timber exposed to fires.

Model	Positioning	Applicability	Limits
EC 5 type (K&W [25] and M&B [23, 28, 70])	Semi-empirical, calibrated to SF/PF furnace tests	Reliable for 1D section response under SF/PF	Without heat generation from timber burning
TiCHS [26]	Energy-based time- equivalent approach	Captures decay-phase heating	Without heat generation from timber burning
Gpyro [65]	Mechanistic pyrolysis chemistry with coupled mass/energy transport	High accuracy for local phenomena and oxidation	Heavy data calibration and high computational cost
Hopkin [66]	Heat of hydration principle	Simple and fast	Requires calibration and broader validation for diverse non-standard fires
Floyd & Hodges [67]	Scaling-based engineering models	Multi-scale and multi- material	Limited testing scenarios (not modern large-open compartments); Real-compartment boundary conditions not fully covered

2.3 A simple heat generation model to consider timber combustion

To simplify and visualize the consideration of absorbed heat ($\dot{q}_{comb_in}''$) when the char layer undergoes smouldering and being engulfed by surface flames, it is necessary to introduce a new method. The method was derived from a series of tests with the help of the Heat-Transfer Rate Inducing System (H-TRIS) [71], which was originally developed at University of Edinburgh. The H-TRIS established at Hong Kong Polytechnic University was employed in the present study, which is equipped with radiant panel matrix and electronically controlled moving rails. It allows for the time-varying heat fluxes on the exposed surface, which can be used to approximate various non-standard fire actions.

2.3.1 H-TRIS Series Tests for deriving Heat Generation Model

2.3.1.1. Pre-test Procedure for Incident Heat Flux Uniformity Verification (Q_{fire1} vs Q_{fire2})

Two water-cooled heat flux gauges were calibrated under different heat flux conditions to measure incident radiative heat flux on the sample surface, Q_{fire1} and Q_{fire2} , respectively. For all verifications, the sensing faces were oriented parallel to the radiant panel. To avoid the influence of accumulated thermal gas around the heat flux gauges, based on the experience of Maluk et al. [72], the distance between the exposed surface of the rock wool board and the surface of the heat flux gauge inserted at its internal opening was set to 2 mm for calibration work. The corresponding experimental setup and layout are shown in Fig. 2.3. The calibration coefficients supplied by both gauge manufacturers were recorded for post-processing prior to use. The comparison in Fig. 2.3d confirms that, based on these calibration coefficients, the two gauges accurately measure the same incident radiant heat fluxes (within $\pm 2\%$) within the entire 0-125 kW/m² calibration range.

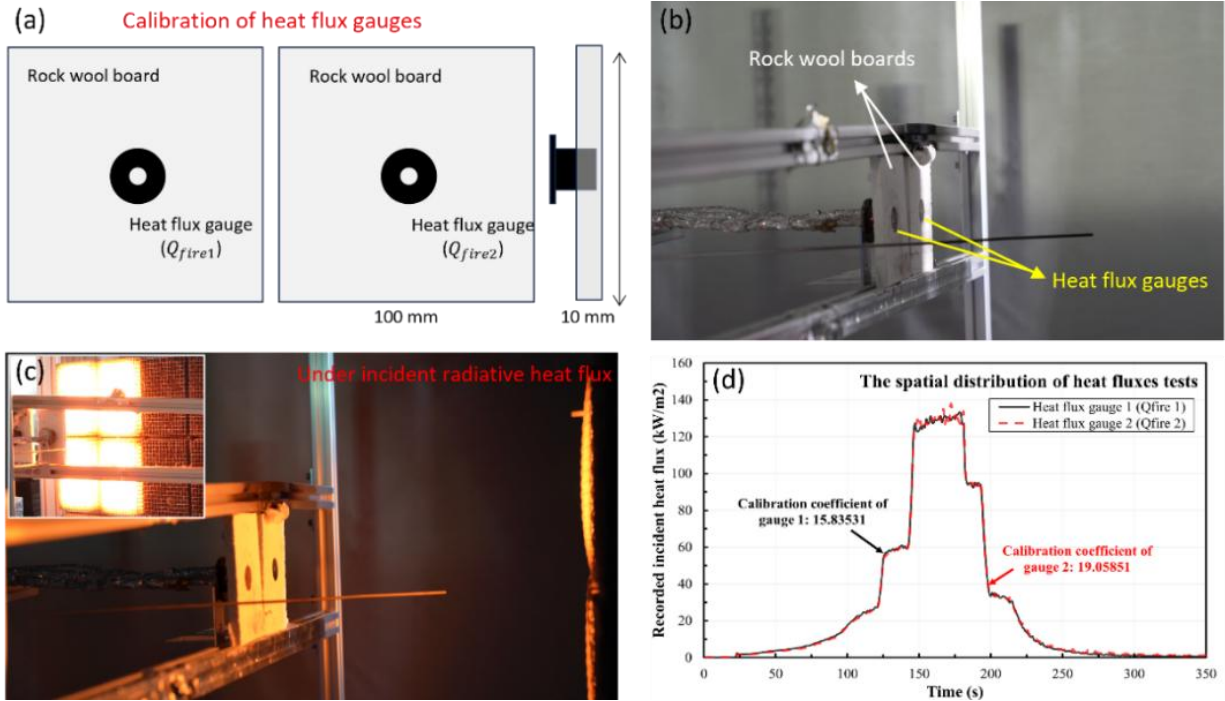


Fig. 2.3. Calibration procedure for heat flux gauges: (a) Schematic diagram of the pre-test device; (b) Experimental setup diagram; (c) Calibration under incident radiative heat flux applied by radiant panel; (d) The uniformity verification tests results for the two heat flux gauges used.

2.3.1.2. Incident vs Received Heat Flux Definitions (Q_{fire} vs Q_{total})

To quantify the heat transferred internally during the combustion process of timber, the tests were conducted by keeping the left side of the apparatus constant and replacing the right side with a timber block. A heat flux gauge was inserted into a pre-made hole to measure the heat flux, as shown in Fig. 2.4a and

2.4b. Subsequently, a series of tests were conducted to study the burning effects of timber under different fixed heat flux conditions for both components simultaneously. In this case, the reading of the heat flux gauge on the left side (rock wool board) is recorded as Q_{fire} , which represents the incident radiant heat flux received at different distances. The reading of the heat flux gauge on the right side (timber block) is recorded as Q_{total} , representing the heat effectively absorbed by the timber for the same incident radiant flux by considering the effects of timber combustion. Considering the gauge measured heat fluxes largely represent the flux components perpendicular to its surface, this may underestimate the heating contribution from timber burning and especially the oxidation of char layer.

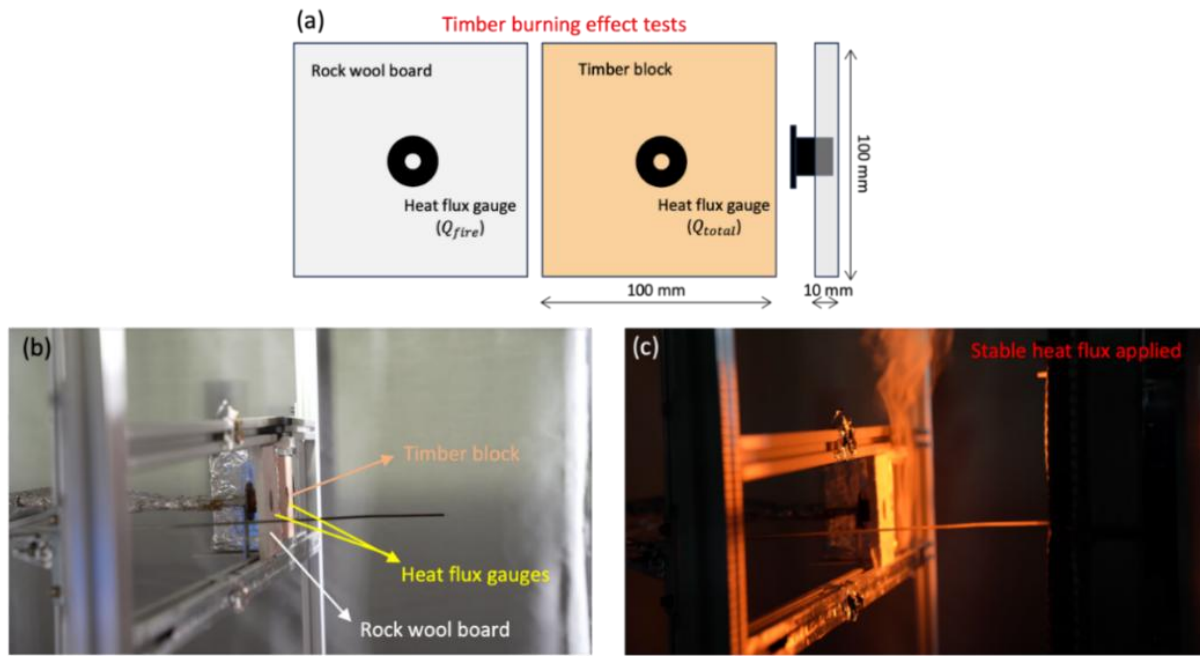


Fig. 2.4. Tests for quantifying the burning effects of timber: (a) Schematic diagram of the test device; (b) Experimental setup diagram; (c) Stable incident radiative heat flux applied by H-TRIS.

2.3.2 Newly Conducted Tests on Timber Sections Exposed to Non-standard Fires for Validation

To investigate the effect of heat generation during timber combustion and to provide a more challenging case for validating the developed model, the newly conducted test under non-standard fire (NSF) actions characterized by varying heat flux has been conducted on European beech specimens with dimensions of 100 mm × 90 mm × 80 mm (Length × Width × Thickness) and modelled by using OpenSees for fire in this chapter. The blocks were mounted 150 mm in front of the H-TRIS radiant panel, which delivered time-varying incident heat fluxes in the 0 - 125 kW/m² range under fully automatic power and rail control. Each specimen was oriented so that its 100 mm × 90 mm face was parallel to the panel. The remaining five faces were wrapped with 10-mm-thick aluminosilicate ceramic fibre and aluminum foil to maintain approximately one-dimensional (1D) heat transfer, as shown in Fig. 2.5b.

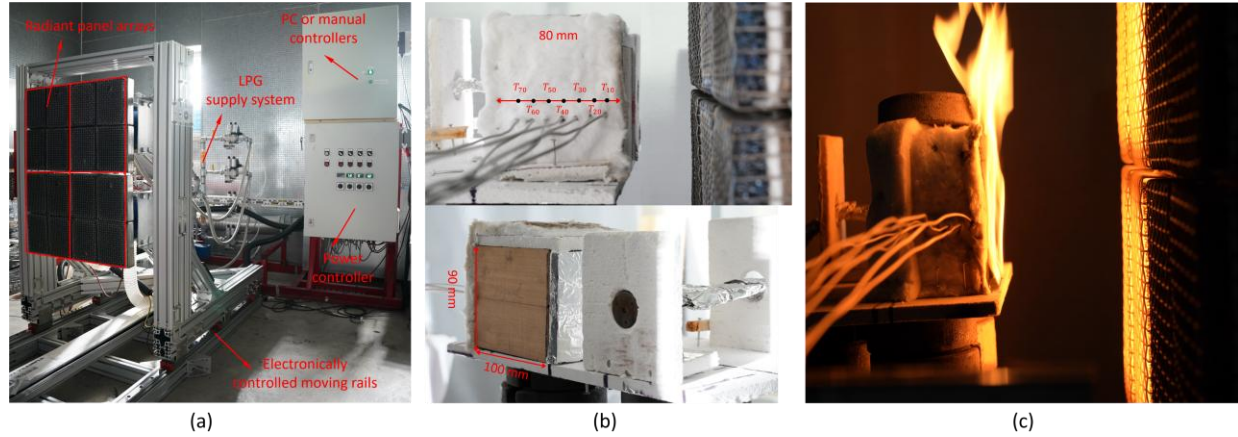


Fig. 2.5. A newly conducted non-standard fire test using H-TRIS radiant panels: (a) H-TRIS panels at Hong Kong PolyU; (b) A typical specimen with side insulation and thermocouples layout; (c) Flames at the timber surface during heating exposure.

Prescribed heat fluxes, varying over time in the 0 -125 kW/m² range, were applied to the timber blocks using the H-TRIS system's automatic rail and power control system. Type K thermocouples consisting of a 1.0 mm diameter thermocouple bead, adjacent metallic lead behind the connection point, and a stainless-steel sheath, arranged as shown in Fig. 2.5b, were installed 10, 20, 30, 40, 50, 60 and 70 mm from the exposed surface in timber section to record the temperature evolution. All sensing tips were embedded to depth of 50 mm by drilling 1.8 mm-diameter holes, inserting the junctions to depth, and backfilling the holes with ceramic paste to insulate. The sheathed leads were routed through an external layer of rock-wool insulation on the side surface. It should be noted that the setup of this experiment may not fully prevent the minor heat conduction from adjacent metallic lead or stainless-steel sheath of the thermocouple along the lead path into the timber section, which may cause discrepancies compared to the real timber sections. The average density of tested specimens in an ambient environment is 730 kg/m³. The moisture ratio is 10.88% (samples with a sample variance of 6.31×10^{-5}), which is measured using specimens from the same batch regarding the initial weight G_0 at the ambient environment and the dry weight G_d after 24 hours of oven drying.

2.4 Model development

2.4.1 Governing Equations and Boundary Conditions

The modelling of heat transfer in timber sections can be achieved in finite element software. The governing equation of it at element level is usually written in the following form [73]:

$$K_e T + C_e \dot{T} = Q_e \quad (2.2)$$

where K_e represents the conductive matrix of a finite element, and C_e is the thermal capacity matrix comprising specific heat c_p and density ρ . T is a vector of nodal temperature, $\dot{T}$ indicates the temperature

increment vector at the nodes, and Q_e represents the heat received at the element surfaces or internally generated, which can be estimated using the following equation:

$$Q_e = \int_S q_S \cdot dS + \int_V q_V \cdot dV \quad (2.3)$$

where q_S is the external heat flux vector received by the element if surface (S) heat fluxes exist. The volume heat q_V represents the internal volume (V) heat to separately consider the generated heat during the char oxidation of the timber section in this chapter, which contrasts with the heat consumption of temperature rise corresponding to the heat capacity $C_e \dot{T}$.

Furthermore, due to the complexity of physical changes and chemical reactions during the combustion process of timber, it is difficult to estimate the heat generated by timber combustion itself. As discussed previously, the heat generated by timber combustion ($\dot{q}_{comb_out}''$) in the form of flaming and smouldering is largely released to the surrounding environment. Based on engineering simplification, this study relates the heat generated by the charring process and the received heat on the surface through the heat generation model. This allows for an accurate and quick assessment of the impact of timber combustion. Therefore, when considering the effect of timber combustion, Eq. 2.3 can be rewritten as:

$$Q_e = \int_S q_S \cdot dS + \int_S k q_S \cdot dS \quad (2.4)$$

where k is the coefficient of variation which varies with the external incident heat flux and the corresponding variation follows the rules of the proposed heat generation model.

2.4.2 Implementation in OpenSees (phase-tag logic & cooling treatment)

As a leading open-source simulation framework, OpenSees [74] has been extended for modelling structures in fire [49]. In addition to the thermo-mechanical codes developed for structure responses, a transfer analysis module associated with a fire module has been added to the OpenSees for fire [49]. The HT analysis module has been equipped with Tcl and Python and validated previously [48].

In this chapter, the above-discussed heat transfer model for timber is now implemented into the OpenSees heat transfer module and can be employed to model the temperature evolution in mass timber sections or timber-steel composite sections exposed to fire as shown in Fig. 2.6a. Additionally, in Fig. 2.6b, a state determination process is given for the heat transfer model. At each Gaussian Integration point of the finite element, a Phase Tag (Ptag) is assigned to the material model to record the current layer state corresponding to the various layers of timber section: the virgin layer (0), the dehydration layer (1), the pyrolysis layer (2), and the char layer (3). At each fire step n , the trial temperature of the timber material will be updated with the trial ΔT after each iteration and the trial phase tag remains the committed tag. This will be checked against the phase transition conditions (critical temperature as mentioned earlier) to update

the layer state. In the cases of unchanged phase tag, the timber temperature will be compared to identify whether it enters a cooling stage. If yes, the timber layer will remain as the previously recorded state and its thermal properties will be taken as the committed values. If heating continues, the timber properties will be determined according to the updated phase tag and the trial temperature. These parameters will be set as committed values while the eventual convergence is fulfilled for the current load step.

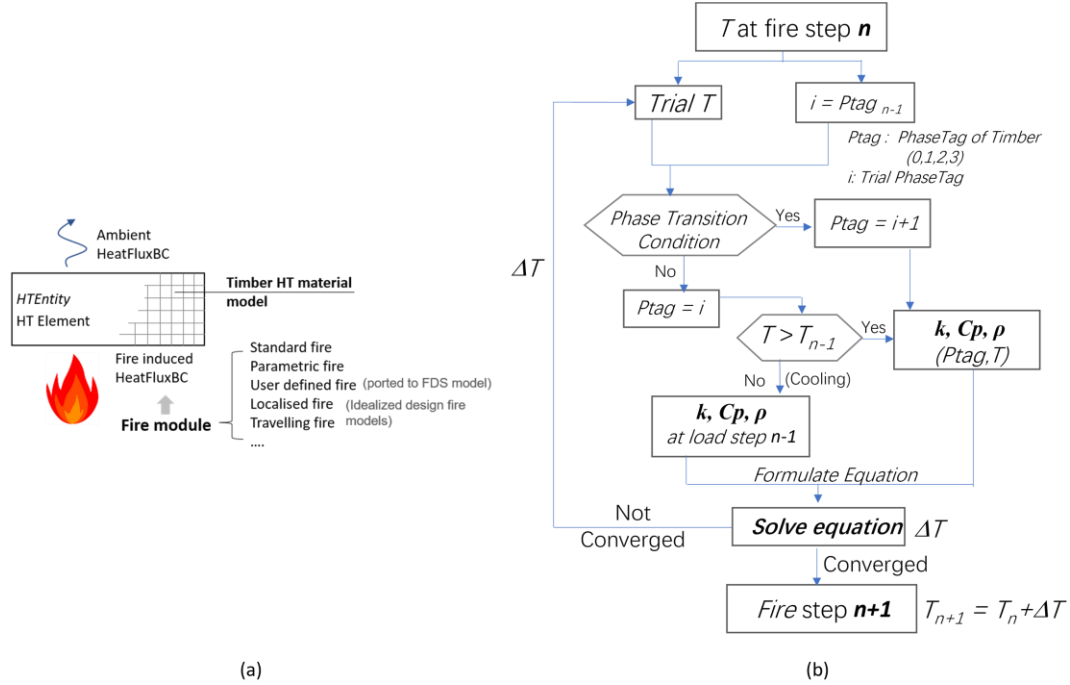


Fig. 2.6. Implementation of timber heat transfer material model based on finite element method: (a) Schematic of a heat transfer model; (b) State determination in FEM framework.

2.4.3 Minimum-Input Layered Thermal Property Model

2.4.3.1. Minimum-Input Parameterization

To minimize the input of timber properties, the transitions of each thermal property are prescribed using linear curves, or the EC5 recommended variation when a specific input is not present. The model therefore requires only three baseline inputs at room temperature (20 °C by default): k_{20} for thermal conductivity, c_{p20} for specific heat, and ρ_{20} for density.

Linearization is imposed for the implementation of temperature-based variation in OpenSees for fire, and all variations at elevated temperatures are controlled by these input parameters together with the prescribed transition curves (see Fig. 2.7, Table A.2.1- C_p , Table A.2.1- ρ and Table A.2.1- k in the Appendix). Unlike traditional approaches that rely solely on temperature, the proposed scheme assigns properties by a dual criterion, current temperature, and the layer state, so that the section response remains well-posed during heating and cooling in realistic fires. The following subsection details the layered property laws and tag-based transitions

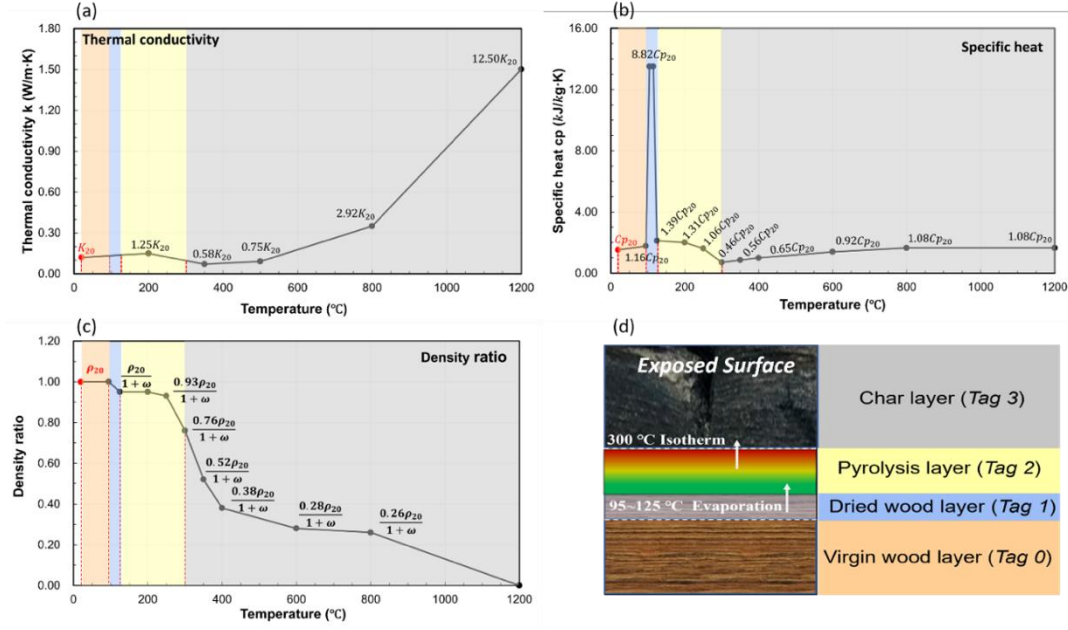


Fig. 2.7. Minimum-input parameterization of timber thermal properties and layered-state definition: (a) Thermal conductivity k ; (b) Specific heat c_p ; (c) Density ratio ρ/ρ_{20} ; (d) Schematic of layer tags and temperature thresholds for timber section exposed to fires.

2.4.3.2. Layered-State Property Laws and Transitions

For thermal conductivity, the k_{20} was used as the control input parameter and adopt multi-segment bilinear curves that follow the EC 5 conductivity variation from 20 °C to 1200 °C. For specific heat, the input parameter c_{p20} is offered to allow flexible definition while generally following the EC 5 trend. For the purpose of finite element convergence, only the temperature range during the water evaporation stage was modified from the 99 °C – 99 °C (peak) – 120 °C (peak) - 120 °C to 95 °C – 105 °C (peak) – 115 °C (peak) - 125 °C [50, 75]. In detail, the specific heat increases linearly from c_{p20} to $1.16c_{p20}$ at 20 °C to 95 °C, which is followed by a linear surge to $8.86c_{p20}$ representing the massive heat consumption due to evaporation (105 °C - 115 °C). A liner declines from $8.86c_{p20}$ to $1.39c_{p20}$ at 125 °C indicates the completed drying process. The density variation adopts an identical model as recommended in EC5, which depends on the original wood density ρ_{20} and moisture ratio w . Except for the specific-heat adjustment around evaporation, the thermal properties of timber (k , c_p , and ρ) are thus taken from existing layered property models [23, 25, 28, 70] and EC5 and consistently parameterized by (k_{20} , c_{p20} , and ρ_{20}) without case-by-case calibration.

Based on the transition conditions between different stages of timber pyrolysis, layer tags are used in the proposed heat transfer model to record the distribution of characteristic layers within the timber cross-section during a fire. The thermal properties of each characteristic layer would be based on its temperature and layer tag. For the transition conditions, the change from the virgin layer (*Tag 0*) to the dehydration layer (*Tag 1*) is determined by the evaporation temperature of 95 °C and the dehydration process is completed in

the range of 95 °C to 125 °C. Upon completion of dehydration, the dehydration layer (*Tag 1*) transforms into the pyrolysis layer (*Tag 2*), which starts the initial slow pyrolysis. The critical temperature for determining the transition to the char layer (*Tag 3*) is assigned as 300 °C, as it is usually recommended in the literature for identifying the char front. Once the transition between layers is achieved, no backward transition should be allowed, and the layer state tag will remain as the higher one, e.g., the formed char layer cannot be regressed to a wood layer. Consequently, the thermal properties of each layer are based on its temperature and tag, and during cooling the variables are determined by the past maximum temperature (“peak-temperature locking”) in each layer state. This ensures that the char formed during the heating stage (*Tag 3*) retains the appropriate properties during subsequent cooling, preventing unphysical rollback and enabling accurate, quick assessment of heat transfer under non-standard fires with cooling.

For application, the key input parameters are defined according to consistent principles, (k_{20} , c_{p20} , and ρ_{20}) for the base material and w when density-moisture coupling is needed, while any missing temperature dependence defaults to EC5. Case execution then simply selects the material baselines and boundary conditions, after which the prescribed curves and layer tags govern the full-range property transitions (20 – 1200 °C) without specific calibration for each modelling case.

2.4.4 Heat Generation Model to Consider Timber Burning Effect

Timber, as a typical charring material, can sustain both flaming and smoldering combustion and once ignited, timber elements in compartments contribute significantly to the overall heat release rate and potentially affect the fire resistance of the overall structure. The tests mentioned in Section 2.3.1 above explored the values of the external incident heat flux (Q_{fire}) and the received total heat flux (Q_{total}), which aims to establish a protocol of a simple heat generation model to be integrated in the heat transfer model of timber sections subjected to non-standard fires, as shown in Fig. 2.8a. Specifically, the maximum Q_{fire} in the heat-generation model was limited to 125 kW/m², corresponding to the highest measured surface heat flux of the present H-TRIS setup. Furthermore, based on the characteristics of the test data distribution, the overall fitting of the relationship curves when Q_{fire} changes within the 0~125 kW/m² heating stage and 125~0 kW/m² cooling stage, and the formula of the trend fitting curve is shown in Eq. 2.5, respectively,

$$Q_{total} = \begin{cases} 3.40e^{-5}(Q_{fire})^3 - 3.75e^{-3}(Q_{fire})^2 + 1.27Q_{fire}, & 0 < Q_{fire} < 125 \\ 6.67e^{-8}(Q_{fire})^5 + 2.15e^{-5}(Q_{fire})^4 - 2.44e^{-3}(Q_{fire})^3 + 0.11(Q_{fire})^2 + 0.42Q_{fire}, & 125 > Q_{fire} > 0 \end{cases} \quad (2.5)$$

In general, this model simplifies the complex changes in the timber-burning process and quantifies the thermal effect of timber combustion. For example, as shown in Fig. 2.8b and 2.8c, when the Q_{fire} reaches 50 kW/m² in the heating stage from 0 to 125 kW/m² and the cooling stage from 125 kW/m² to 0, the Q_{total} are 58 and 95 kW/m², respectively. Therefore, their corresponding timber combustion heat release $Q_{combustion}$ are 8 and 45 kW/m², respectively.

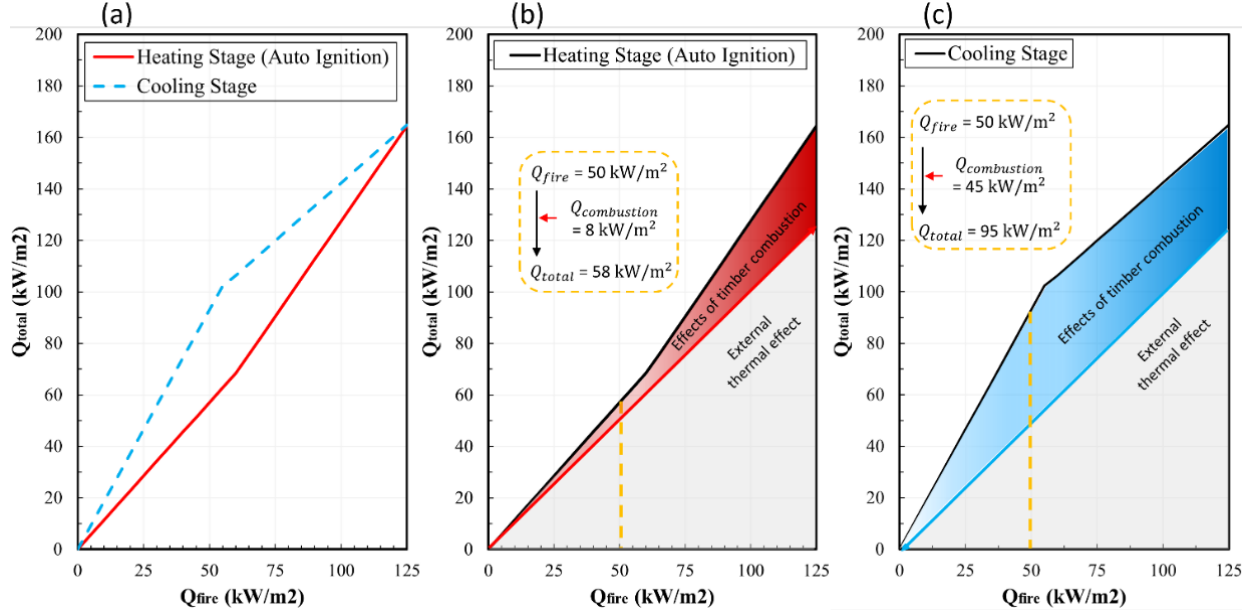


Fig. 2.8. Proposed heat generation model: (a) Relationship between the external incident heat flux (Q_{fire}) and the received total heat flux (Q_{total}) during heating and cooling stages; (b) Diagram during the heating (Auto ignition) stage; (c) Diagram during the cooling stage.

It is noteworthy that during the cooling phase of the test, while the heat flux gauge wrapped in rock wool board detected a rapid decrease in the incident heat flux Q_{fire} , the detection value Q_{total} of the heat flux meter wrapped in timber block remained stable for a period until Q_{fire} dropped to 110 kW/m² before decreasing. This may be due to lagging heating sustained by timber burning despite the reduction of the external heat source. This continued temperature rise during the cooling phase may be due to the lagging heat from timber combustion (smouldering char) despite the reduction of the external heat source. Additionally, even after combustion ceases, ongoing heat transfer and moisture redistribution within the timber can contribute to further delayed failure. These combined effects can potentially result in structural damage or even delayed failure of timber components (for instance, delayed failure of a timber column was observed in [19] and delayed smouldering damage of timber ceilings in large-open timber compartments [68]). However, the current EC5 model and EC5 type model only apply to standard fire exposure and cannot predict the thermal response of timber components in real fire scenarios with non-standard fire actions. Therefore, the proposed model considers the effects of timber burning on internal heat transfer within the cross-section of timber components during the decay phase, thus improving the fire safety performance of timber structures through more accurate thermal response prediction.

In addition, non-linear models are typically more complex, and simplifying non-linear models into linear versions is an important technique in engineering applications, providing tools that are easier to handle and analyze. Therefore, as shown in Eq. 2.6, the linearized simplified version of the proposed heat

generation model is achieved through the bilinear model, which is more user-friendly for processing and analysis.

$$Q_{total} = \begin{cases} \begin{cases} 1.14Q_{fire}, & 0 < Q_{fire} \leq 60 \\ 1.48Q_{fire} - 20.59, & 60 < Q_{fire} \leq 125 \end{cases}, & \text{heating stage} \\ \begin{cases} 0.90Q_{fire} + 52.31, & 60 < Q_{fire} \leq 125 \\ 1.86Q_{fire}, & 0 < Q_{fire} \leq 60 \end{cases}, & \text{Decay stage} \end{cases} \quad (2.6)$$

2.5 Model validation

2.5.1 The Specific Definition of Thermal Properties Input Parameters for the Validation Cases

The thermal properties of timber have large uncertainties, and various models have been adopted in the literatures [23, 25, 28, 70, 76]. The most commonly used model for the thermal properties of timber is the EC5 model. König and Walleij [25] (K&W model) then modified the EC5 model [76] to simulate spruce specimens exposed to Standard fire (SF) and Parametric fires (PF). Using a detailed Gpyro model, Richter et al. [70] adopted the values in Miller and Bellan's generic wood model (M&B model) [23] to define the thermal properties for different states of timber including virgin layer, dehydration layer, pyrolysis layer and char layer, and estimated the density variation according to mass loss. The values of thermal properties at characteristic temperatures have been listed in Table 2.2. It can be found that the thermal conductivity values are similarly defined at each characteristic temperature.

Table 2.2. Thermal properties defined in previous literatures and Eurocode [23, 25, 28, 70, 76].

	EC5 model [76]			K&W model [25]			M&B model [23, 28, 70]		
Characteristic temperature	Density ratio	k_i (W/m-K)	c_{pi} (J/kg-K)	Density ratio	k_i	c_{pi}	Density ratio	k_i	c_{pi}
20 °C	1+ ω	0.120	1530	1	0.120	1520	1	0.126	2300
125 °C	1	0.133	2120	0.890	0.135	1640	-	-	-
300 °C	0.76	0.097	710	0.720	0.097	1167	0.349	0.084	1100
600 °C	0.26	0.350	1650	0.625	0.350	690	0.013	0.800	880

The above-mentioned models have been illustrated in Fig. 2.9, where the input parameters (Table 2.3) used in the thermal property of the developed OPS model (Table A.2.1- C_p , A.2.1- ρ and A.2.1- k in Appendix) for non-standard fire (NSF) actions are based on the model values provided in the EC5 only after adjustment according to the relationship between the conductivity and the wood density [77] while variations in density and specific heat follow the EC5 model. For the M&B model associated with different

layer states, the thermal properties according to temperature have been plotted as stepwise variations. It should be pointed out that the definitions of thermal property models remain identical for parametric fires (Case PF-Spruce) and NSF scenarios (Case NSF-beech), whereas the differences only appear in the input parameters such as density, moisture ratio, and the associated changes of thermal conductivity based on density [77]. Moreover, these thermal property variations have been integrated into the open-source implementation so as to not require repeated or complex input from users.

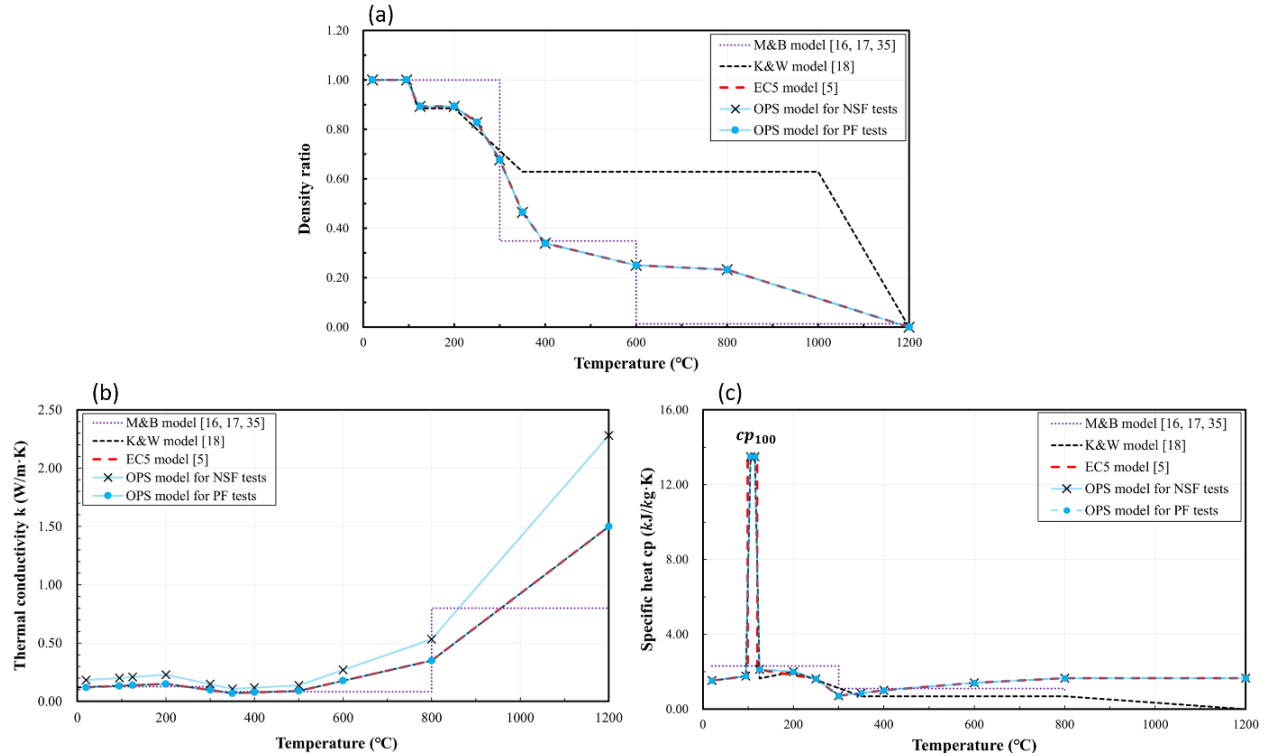


Fig. 2.9. Thermal properties relationship of timber in literatures and this chapter: (a) Density ratio ρ/ρ_{20} ; (b) Conductivity k ; (c) Specific heat c_p .

Table 2.3. Input parameters for timber tests in this chapter [25].

Variables Cases	Moisture content (%)	Conductivity k_i (W/m·K)	Density ρ (kg/m ³)	Specific heat c_{pi} (J/kg·K)
	ω	k_{20}	ρ_{20}	c_{p20}
PF-Spruce	11.45	0.120	480	1520
NSF-beech [0~125 kW/m ²]	10.88	0.183	730	1520

2.5.2 Validation against Previous Reference Parametric-fire Tests (König & Walleij)

Heat transfer models for the tested specimen are now built in OpenSees for fire, which is capable of 1D, 2D, and 3D heat transfer analyses. A 2D model [48] is used here, and the mesh size along the thickness (depth) is chosen as 1 mm, which can produce nearly identical results compared to the models of finer mesh sizes such as 0.25 mm or 0.5 mm based on sensitivity analysis. For defining the thermal boundaries, the convective heat transfer parameters h is 25 W/m²K on the exposed surface and 1 W/m²K on the unexposed surface. The former is recommended by König and Walleij [25] for modelling in the literature. The transient analysis using central difference and a time step of 0.5s is adopted. Due to a single layer of rock wool board insulating the unexposed surface, only very low convection is applied with h as 1 W/m²K. The emissivity of the exposed timber surface is set as 0.8 [78], whereas no radiation is calculated on the unexposed surface because of insulation. However, the emissivity changes with the phases of the timber surface from virgin wood to burned-out char layer, which were recommended as 0.70 and 0.95 [24, 79].

The PF time-temperature curves imposed as boundary conditions (Fig. 2.10a and 2.10b) are the PF-C3 series and PF-C4 series histories reported by König and Walleij [25]. Both curves from tests in a small-scale furnace with internal dimensions 1 m × 0.6 m × 0.6 m (length × width × depth), where the heating profile was defined by the fire load density in MJ/m² related to the total area of the enclosure of the fire compartment and the opening factor in m^{1/2}. The fire curve for PF-C3 assumes a fire load density of 170 MJ/m² and an opening factor of 0.04 m^{1/2}, while PF-C4 assumed a fire load density of 510 MJ/m² and an opening factor of 0.12 m^{1/2}. During the tests, the furnace temperature enters a decay stage after reaching its peak, which was 820 °C in test C1, C2 and C3 (named C3 series) and 1050 °C in test C4, C5 and C6 (named C4 series). Based on the heat generation model with the incident radiant heat flux on the surface of the timber as a reference, the incident radiant heat flux of the furnace gas acting on the surface of the timber is calculated by heat transfer equation and transformed into the total received heat flux taking into account the timber combustion, which is then defined as an external input file and called in the fire model command of OpenSees for fire.

As shown in Fig. 2.10c and 2.10d, with the heat transfer model using the above-described conditions along with the input parameters listed in Table 2.3, the predicted thermal responses of timber sections remain close to the test data at each depth, which showcases the feasibility study of the present heat transfer model for parametric fires. Among these two cases, relatively larger discrepancies can be observed in the C4 series. The main difference is in the dehydration stage, i.e., the 95~125°C temperature interval, which may be due to the higher actual moisture content of the test samples, while the definition of the specific

heat values for this stage in the simulation is based on the moisture content reported in the literature [25] and EC5 recommended values, which leads to a lag in the temperature rise at each depth. In both cases, the temperature at 6 mm decreases following the decline of furnace temperature. The increment of charring depth slows down after one hour of exposure.

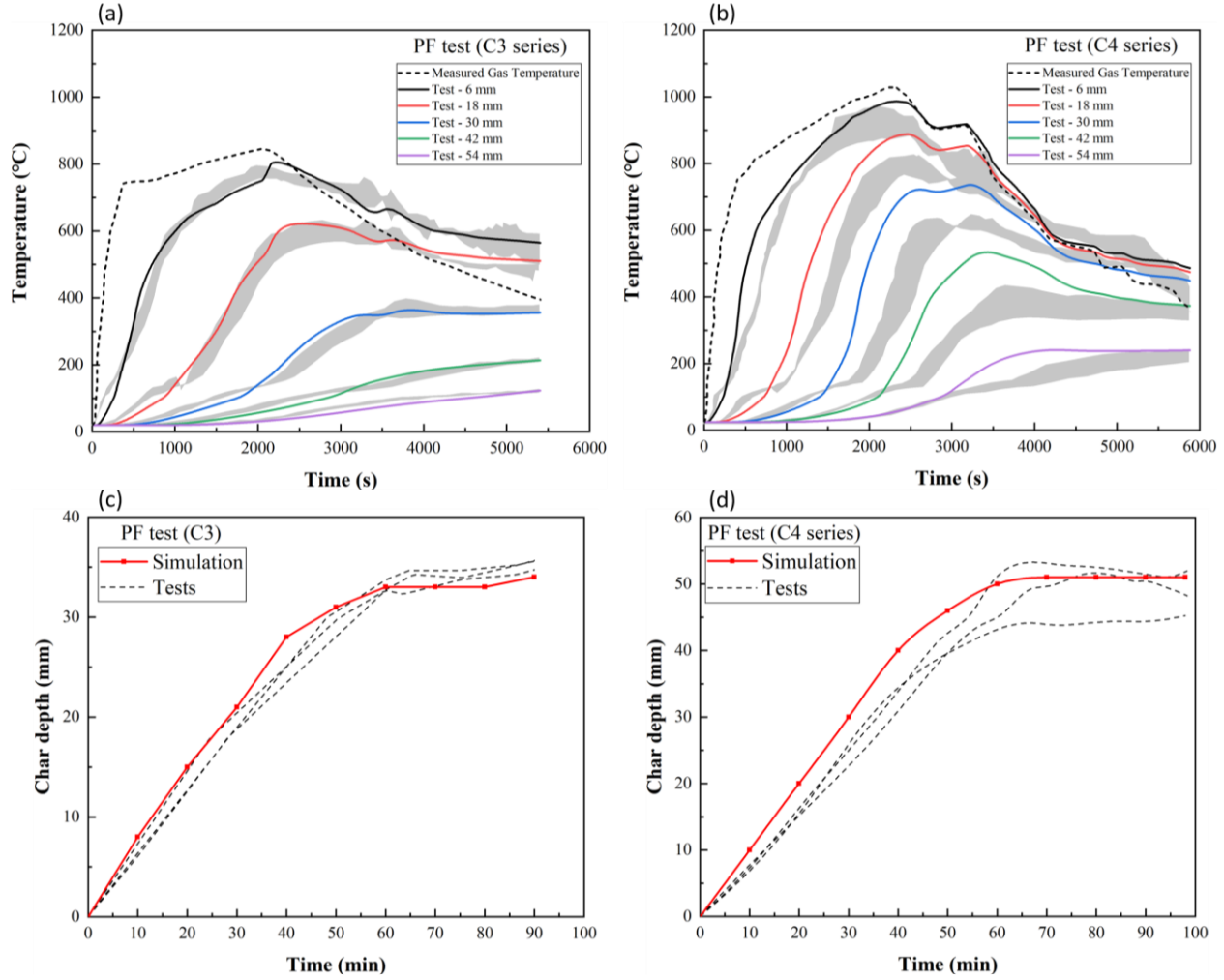


Fig. 2.10. Thermal response of C3 series and C4 series [25] specimens under the parametric fire: (a) Temperature evolution of C3 series; (b) Temperature evolution of C4 series; (c) Charring depth of C3 series; (d) Charring depth of C4 series.

2.5.3 Validation against Newly Conducted H-TRIS Time-variant Heat-flux Tests

The non-standard fire (NSF) scenarios are extended to the time-variant heat fluxes as shown in Fig. 2.11a, which was obtained through varying the power control and panel locations of H-TRIS as described in Subsection 2.3.2. Based on the proposed heat generation model in Subsection 2.4.4 and the incident heat flux (Q_{fire}) applied to the timber block, the applied heat fluxes (Q_{total}) used for heat transfer analysis under non-standard fire actions after considering heat release from timber combustion are shown

in Fig. 2.11b, where the data exceeding the upper limit of the model are extrapolated based on linear fitting. Furthermore, with the heat transfer model using the above-described conditions along with the input parameters listed in Table 2.3, the estimated thermal response of the timber section subjected to prescribed non-standard fire (NSF) action of nearly 3200 s are shown in Fig. 2.11c.

As can be seen from the temperature evolution, the simulated values at 20 mm are a little larger than the tested value between 500 s and 1200 s. This may be because the finite element simulation based only on the defined thermal properties cannot reflect exactly the same physical changes, such as shrinkage and cracking, which causes large errors. In addition, in view of the data fluctuation of the thermocouple during the 800 ~ 1400 s, the failure of the corresponding equipment is also possible. Compared with the test measured data at other thermocouple depths, the heat transfer model has been able to predict well-agreed temperature evolution, except for the removed 30 mm thermocouple with faulty. The above comparison shows that the present model can be used to predict the temperature distribution in the timber cross-section under non-standard fire actions.

Within OpenSees for fire, additional output has been developed for the timber material so that each finite element carries a phase tag, allowing users to track the real-time distribution of virgin wood, dehydration, pyrolysis, and char through the section. Fig. 2.11d is generated directly from these tags and reports the layer proportions at 0, 600, 1800, 2400 and 3000 s, with coloured columns representing the four states. While the pyrolysis layer is thinner than the char layer at any given time, Fig. 2.11d shows that during the decay (cooling) stage the growth of char slows, whereas the dehydration and pyrolysis layers continue to expand in relative proportion. This behaviour indicates that, even as external heat flux decreases, thermal inertia in the heated outer region sustains inward heat conduction and the effect of heat generation from timber combustion drives further moisture evaporation and decomposition deeper into the timber. The result is a lag between surface exposure and internal degradation, such that the greatest affected depth may occur after the peak heating stage. From the perspective of materials, dehydration and pyrolysis substantially reduce stiffness and strength before timber converts char, so the zero-strength layer extends beyond the visible char depth. The continued growth of dehydration and pyrolysis during cooling therefore enlarges the ineffective cross-section and can markedly reduce residual capacity, especially in long-decay fires where heat has more time to penetrate. Designs or assessments that consider only the heating phase risk underestimating post-fire damage depth and overestimating residual strength. Accordingly, performance-based evaluations should include the full natural fire curve, including decay, and explicitly check residual section and stability at the end of cooling stage. Overall, the post-peak increase of dehydration and pyrolysis layers captured by the proposed functions of the phase-tag output reflects real physical processes in timber under natural fire.

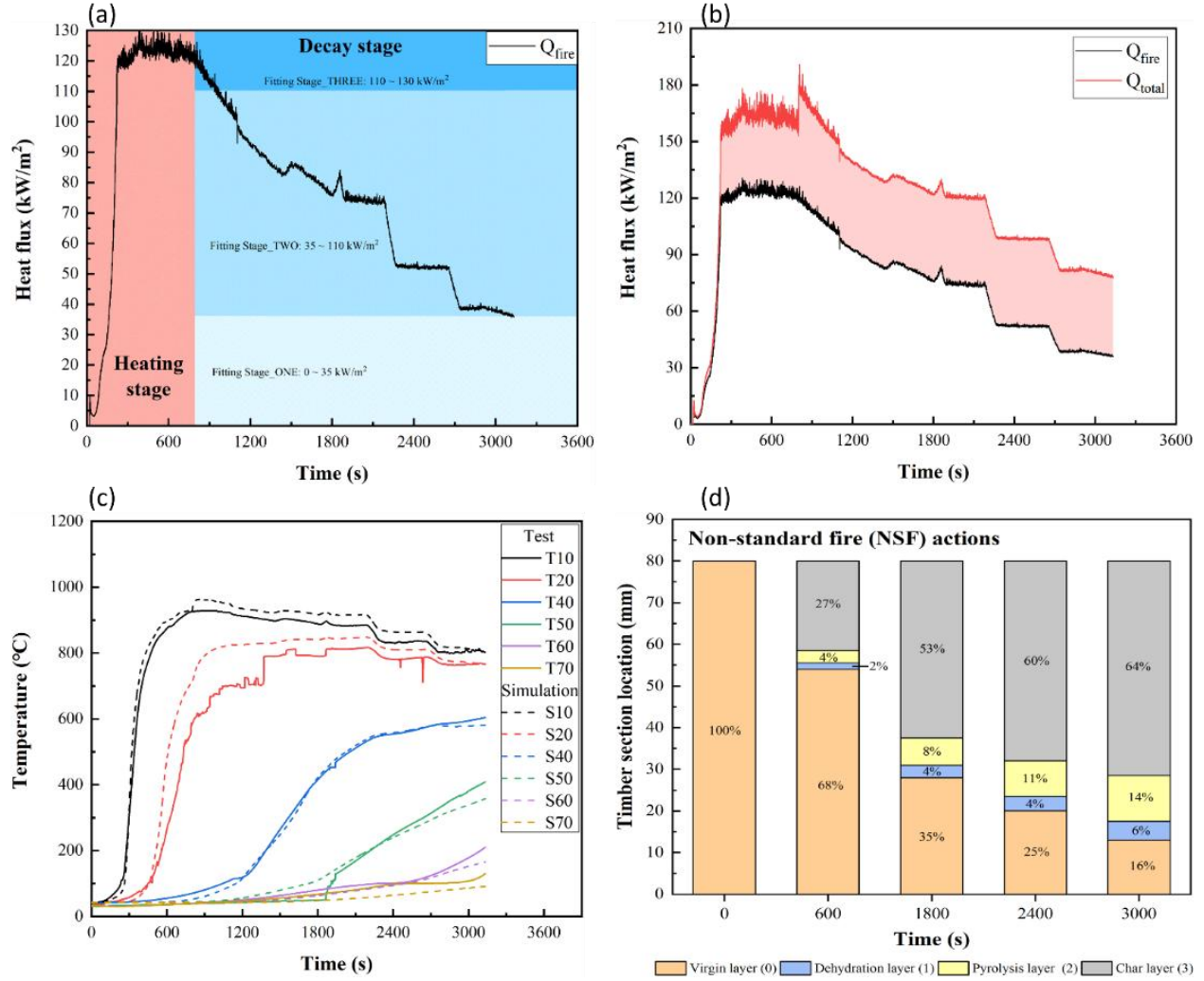


Fig. 2.11. Thermal response of C3 series and C4 series [25] specimens under the parametric fire: (a) Temperature evolution of C3 series; (b) Temperature evolution of C4 series; (c) Charring depth of C3 series; (d) Charring depth of C4 series.

2.6 Discussion on Modelling Thermal Response of Timber Section in Fire

The developed heat transfer model for timber sections subjected to non-standard fire actions has been validated. It is necessary to clarify that the limitations of the model exist due to the engineering purpose of this model. The thermal property variation versus temperature has been given based on the literature, and the realistic thermal properties of different timber types may vary. This of course requires more experimental work to achieve a growing database for the broader scope of construction timber. With this model framework, it is possible to develop it further and validate it extensively regarding in-laboratory and full-scale fire tests.

Meanwhile, the realistic fire action to the timber members should be characterized. For fires in modern compartments of more timber components, the fire behavior is significantly affected by the heat released

from timber [30, 45, 68]. The Malveira large compartment fire test [30] has observed a regional flashover following the travelling of the fire and the ignition of timber linings at one end of the long compartment. The FRIC-01 test observed rapid flame spread along timber components in an large-open compartment with cross laminated timber (CLT) and large window opening when the ceiling was ignited, but the compartment did not show full flashover but rather a travelling fire behavior with flashing waves [45]. The CodeRed projects have demonstrated the intensified fire behavior induced by the burning of timber ceilings in a large compartment [68]. In the case that a building comprises timber structural members, the ignition of timber will release a large amount of heat to the compartment environment, and the rate of heat release in the compartment will rise rapidly [80]. Thus, the future fire safety evaluation of timber structural members should consider the actual fire impact, which ideally should include the burning of the timber section in the engineering description of fire behavior.

2.7 Conclusions

This chapter presents a heat transfer model aiming to provide an engineering estimation of the thermal response of timber sections in cases where non-standard fire actions are involved. A heat generation sub-model for internally absorbed heat due to combustion has been proposed and integrated into the heat transfer model. The model has been implemented in the OpenSees for fire, taking advantage of the open-source and object-oriented nature of the finite element simulation platform. An investigative case of thermal boundary conditions for timber exposed to non-standard fire actions has been imposed through H-TRIS and conducted to examine the performance of the proposed heat transfer model. The conclusions of this chapter are drawn as below:

- 1) A heat transfer model for timber sections in non-standard fire actions has been developed to incorporate thermal properties, characteristic layer division, and heat generation models.
- 2) The heat generation models summarized from the tests can be used to effectively assess the amount of heat absorbed within the timber during timber combustion under different fire conditions characterized using different incident radiation heat fluxes imposed by H-TRIS.
- 3) The proposed heat generation model as an engineering-purposed and simplified model compatible with conventional heat transfer analysis modules has been implemented in OpenSees for fire. Non-standard fire actions including the existing parametric fires tests on the spruces and time-variant heat flux test executed on the beech specimen were used to examine the proposed heat generation model integrated in heat transfer models, and the results showed good performance in predicting the thermal response of timber sections. These test scenarios also demonstrate the need of layer state recording and heat generation model for a heat transfer model of timber sections subjected to non-standard fires.
- 4) The present work introduces a framework of engineering heat transfer models for timber sections

exposed to fires. Although more experimental studies being needed to enrich the material libraries regarding the timber type and input parameters, the current heat transfer model now provides a modelling basis for further validation and can be potentially used for simulating timber structures in non-standard fire action.

2.8 Appendix

Table A.2.1- c_p . Piecewise specific heat model $c_p(T)$.

Layer Tag (s)	Temperature range (°C)	Evolution expression for Specific heat (c_p) vs Temp (T) (using c_{p20} as the only input parameter)
Virgin layer (Tag 0)	20 - 95	Linear: $C_p = C_{p20}$ at 20 °C $\rightarrow$ $1.16C_{p20}$ at 95 °C (20 - 95 °C, linear interpolation)
Dehydration layer (Tag 1)	95 - 125	Linear: $C_p = 1.16C_{p20}$ at 95 °C $\rightarrow$ $8.82C_{p20}$ at 105 °C (95 - 105 °C, linear interpolation)
		Constant: $C_p = 8.82C_{p20}$ from 105 °C to 115 °C (105 - 115 °C, remain constant)
		Linear: $C_p = 8.82C_{p20}$ at 115 °C $\rightarrow$ $1.39C_{p20}$ at 125 °C (115 - 125 °C, linear interpolation)
Pyrolysis layer (Tag 2)	125 - 300	Linear: $C_p = 1.39C_{p20}$ at 125 °C $\rightarrow$ $1.31C_{p20}$ at 200 °C (125 - 200 °C, linear interpolation)
		Linear: $C_p = 1.31C_{p20}$ at 200 °C $\rightarrow$ $1.06C_{p20}$ at 250 °C (200 - 250 °C, linear interpolation)
		Linear: $C_p = 1.06C_{p20}$ at 250 °C $\rightarrow$ $0.46C_{p20}$ at 300 °C (250 - 300 °C, linear interpolation)
Char layer (Tag 3)	300 - 1200	Linear: $C_p = 0.46C_{p20}$ at 300 °C $\rightarrow$ $0.56C_{p20}$ at 350 °C (300 - 350 °C, linear interpolation)
		Linear: $C_p = 0.56C_{p20}$ at 350 °C $\rightarrow$ $0.65C_{p20}$ at 400 °C (350 - 400 °C, linear interpolation)
		Linear: $C_p = 0.65C_{p20}$ at 400 °C $\rightarrow$ $0.92C_{p20}$ at 600 °C (400 - 600 °C, linear interpolation)
		Linear: $C_p = 0.92C_{p20}$ at 600 °C $\rightarrow$ $1.08C_{p20}$ at 800 °C (600 - 800 °C, linear interpolation)
		Constant: $C_p = 1.08C_{p20}$ from 800 °C to 1200 °C (800 - 1200 °C, remain constant)

Table A.2.1- ρ . Piecewise specific heat model $\rho(T)$.

Layer Tag (s)	Temperature range (°C)	Evolution expression for Density (ρ) vs Temp (T) (using ρ_{20} as the only input parameter) * ω : moisture content, inherent parameter of timber
Virgin layer (Tag 0)	20 - 95	Constant: $\rho = \rho_{20}$ from 20 °C to 95 °C (20 - 95 °C, remain constant)
Dehydration layer (Tag 1)	95 - 125	Linear: $\rho = \rho_{20}$ at 95 °C $\rightarrow \frac{\rho_{20}}{1+\omega}$ at 125 °C (95 - 125 °C, linear interpolation)
Pyrolysis layer (Tag 2)	125 - 300	Constant: $\rho = \frac{\rho_{20}}{1+\omega}$ from 125 °C to 200 °C (125 - 200 °C, remain constant)
		Linear: $\rho = \frac{\rho_{20}}{1+\omega}$ at 200 °C $\rightarrow \frac{0.93\rho_{20}}{1+\omega}$ at 250 °C (200 - 250 °C, linear interpolation)
		Linear: $\rho = \frac{0.93\rho_{20}}{1+\omega}$ at 250 °C $\rightarrow \frac{0.76\rho_{20}}{1+\omega}$ at 300 °C (250 - 300 °C, linear interpolation)
Char layer (Tag 3)	300 - 1200	Linear: $\rho = \frac{0.76\rho_{20}}{1+\omega}$ at 300 °C $\rightarrow \frac{0.52\rho_{20}}{1+\omega}$ at 350 °C (300 - 350 °C, linear interpolation)
		Linear: $\rho = \frac{0.52\rho_{20}}{1+\omega}$ at 350 °C $\rightarrow \frac{0.38\rho_{20}}{1+\omega}$ at 400 °C (350 - 400 °C, linear interpolation)
		Linear: $\rho = \frac{0.38\rho_{20}}{1+\omega}$ at 400 °C $\rightarrow \frac{0.28\rho_{20}}{1+\omega}$ at 600 °C (400 - 600 °C, linear interpolation)
		Linear: $\rho = \frac{0.28\rho_{20}}{1+\omega}$ at 600 °C $\rightarrow \frac{0.26\rho_{20}}{1+\omega}$ at 800 °C (600 - 800 °C, linear interpolation)
		Linear: $\rho = \frac{0.26\rho_{20}}{1+\omega}$ at 800 °C $\rightarrow 0$ at 1200 °C (800 - 1200 °C, linear interpolation)

Table A.2.1-k. Piecewise thermal conductivity model $k(T)$.

Layer Tag (s)	Temperature range (°C)	Evolution expression for Conductivity (k) vs Temp (T) (using k_{20} as the only input parameter)
Virgin layer (Tag 0)	20 - 95	Linear: $k = k_{20}$ at 20 °C $\rightarrow$ $1.10k_{20}$ at 95 °C (20 - 95 °C, linear interpolation)
Dehydration layer (Tag 1)	95 - 125	Linear: $k = 1.10k_{20}$ at 95 °C $\rightarrow$ $1.15k_{20}$ at 125 °C (95 - 125 °C, linear interpolation)
Pyrolysis layer (Tag 2)	125 - 300	Linear: $k = 1.15k_{20}$ at 125 °C $\rightarrow$ $1.25k_{20}$ at 200 °C (125 - 200 °C, linear interpolation)
		Linear: $k = 1.25k_{20}$ at 200 °C $\rightarrow$ $0.81k_{20}$ at 300 °C (200 - 300 °C, linear interpolation)
Char layer (Tag 3)	300 - 1200	Linear: $k = 0.81k_{20}$ at 300 °C $\rightarrow$ $0.58k_{20}$ at 350 °C (300 - 350 °C, linear interpolation) Linear: $k = 0.58k_{20}$ at 350 °C $\rightarrow$ $0.75k_{20}$ at 500 °C (350 - 500 °C, linear interpolation) Linear: $k = 0.75k_{20}$ at 500 °C $\rightarrow$ $2.92k_{20}$ at 800 °C (500 - 800 °C, linear interpolation) Linear: $k = 2.92k_{20}$ at 800 °C $\rightarrow$ $12.90k_{20}$ at 1200 °C (800 - 1200 °C, linear interpolation)

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Chapter 3: OpenSees Development for Modelling Timber Structural Members Subjected to Realistic Fire Impact

Summary

Based on the heat transfer model developed in Chapter 2, Chapter 3 advances the OpenSees for fire platform by incorporating a thermomechanical modelling framework to predict the structural behavior of timber components exposed to realistic fire conditions. The chapter begins by extending the heat transfer capabilities to timber-specific structural elements, enabling simulation of fire exposure on both single-sided CLT slabs and three-sided glulam beams. A developed constitutive model for timber at elevated temperatures is introduced, capturing the temperature-dependent degradation of stiffness and strength. The structural response is analyzed by applying the corresponding thermal actions derived from the heat transfer results, allowing direct coupling of thermal gradients to mechanical performance. The chapter also demonstrates a preliminary integration of CFD-derived fire scenarios with OpenSees for fire, highlighting the feasibility of simulating the thermomechanical response of a timber-concrete composite (TCC) slab in a realistic compartment fire. Through these developments, Chapter 3 provides a platform for analyzing the fire resistance of timber members, bridging heat transfer modelling with structural mechanics, and setting the stage for full-scale applications in compartment fire dynamics and performance-based design strategies.

This chapter is based on “[C. Chen](#), L. Jiang*, J. Qiu, M. A. Orabi, W. S. Chan, and A. Usmani (2023). OpenSees development for modelling timber structural members subjected to realistic fire impact. **Fire and Materials**, vol. 47, no. 4, pp. 461–478, 2023, doi: [10.1002/fam.3115](#).”

3.1 Introduction

With the concern of global warming and the pursuit of carbon neutrality, timber appears to be an outstanding alternate to traditional structural materials such as steel and concrete. The major barrier of widely using timber structures is the flammability of wood structural components, which results in additional fire load and charring of timber sections. Regarding the fire safety of timber structures, the current design practice mostly follows the Eurocode 5 [56], which estimates the load bearing capacity of single members with respect to the effective section as the char layer is of nearly zero load resistance. Following this design principle, mass timber structures using engineered timber such as Glued Laminated (Glulam) timber and Cross Laminated Timber (CLT) were vastly implemented in timber building construction and investigations were conducted regarding their fire performance [34, 81-85]. Correspondingly, modelling the fire behaviour of modern timber structural members is of great interest but facing considerable challenges. The charring behaviour of timber sections in a fire is complex, which involves multi-phase physical changes and chemical reaction [24, 25]. The mechanical properties of timber material are different in terms of loading direction (parallel or perpendicular to grain) [54], which is further complicated by the charring propagation and performance degradation at elevated temperature [19, 86].

Loading tests at ambient temperature and furnace fire tests on load-bearing timber structures were the primary means to examine the fire performance of timber structural members. Fragiacomio et al. [34] carried out bending tests at ambient temperature and large-scale furnace fire tests under standard fire conditions on CLT panels (5600 mm × 600 mm × 150 mm), which showed the fracture dominated failure of CLT beam and rapid-growing deflection after 90 minutes of exposure. Wang et al. [82] tested a series of CLT panels of a size 2200 mm × 420 mm × 105 mm, which recorded the internal temperature distribution and mid-span deflection of the timber panel during the standard fire exposure. Bending tests and fire tests were carried out by Dârmon and Lalu [85] on Glulam beams (3500 mm × 180 mm × 440 mm), which showed the temperature evolution of a Glulam beam subjected to three-side fire exposure and the fire behaviour of the beam. Zhang et al. [83] also conducted series of solid timber beams (4000 mm × 100 mm × 200 mm or 4000 mm × 150 mm × 300 mm) with three-side fire exposure using a furnace. In addition, Bai et al. [81] investigated the load-carrying capacity of a CLT wall (2400 mm × 420 mm × 105 mm) exposed to one-side fire. It is noticed that these fire tests were usually prescribed under standard fire condition to comply with design protocol given in Eurocodes [56].

Full-scale fire tests on timber structures are considerably expensive and usually limited by the environmental constraints. Computational solutions are always important alternative means to fire tests for the purpose of research and design of timber structures in fire. Dârmon and Lalu [85] used the nonlinear finite element software SAFIR [87] to develop thermo-mechanical models of wooden beams subjected to standard fire exposure, which successfully reproduces the temperature evolution of the beam section and

the beam deflection induced by fire and load. Menis [88] used the existing 'Concrete Damage Plasticity' (CDP) in ABAQUS [89] to enable the definition of a material model for wood, which considers the orthotropic behaviour of timber material. Fragiaco et al. [34] also adopted ABAQUS to model the fire resistance of CLT timber panels. Recently, Xing et al. [90] built finite element models in *OpenSees* based on the authors' work [49, 91] to simulate the fire performance of timber wall and timber panel exposed to standard fire exposure. The reported work well demonstrated the potential of open-source development and the need of modelling capabilities for timber structures in real fire. Currently, most of thermo-mechanical analyses were conducted on the basis of heat transfer model following EC 5 model, which is only applicable to standard fires without the consideration of heat generation of timber combustion and increased fire impact due to timber burning. Especially in the context of modern building compartments, fire behaviour is found non-uniform and travelling [30]. Hence, continuous development should be introduced to simulation tools for evaluating the realistic fire performance of timber structures.

In this chapter, the recent development on modelling timber structures in *OpenSees* have been introduced and validated, which aims to build a systematic solution for simulating timber member of various types in real fires. A layer-based heat transfer model previously developed for characterising the heat transfer of timber sections to non-standard fires has been implemented for generating thermal action to the thermo-mechanical model. Thermal action definitions for timber slabs of single-face exposure and beams of multi-side exposure are developed to transfer temperature data from heat transfer analysis to thermo-mechanical analysis module. Thermo-mechanical material model for timber has been developed to co-work with the fibre-based beam sections and layer-based shell sections. The performance of the developed models has been validated against test data reported by other researchers [34, 85]. Moreover, a timber-concrete composite slab system subjected to fire impact with a computational fluid dynamics (CFD) model is simulated to demonstrate the use of the developed modelling capability. As mentioned in other sections of this chapter, the numerical solution in the open-source simulation platform *OpenSees for fire* remains preliminary but important, as the fire safety of timber structures is crucial to the wider use of timber buildings. The presented work in this chapter and future development will maintain open-source via the website: opensesforfire.github.io.

3.2 Simulation platform using OpenSees for fire

OpenSees was originally developed as an Open-Source System for Earthquake Engineering Simulation at UC Berkeley [47], which was programmed using an object-oriented language C++ of a modular architecture. Taking advantage of the excellent extendibility of *OpenSees* framework and after years of development, the fire edition of *OpenSees (OpenSees for fire)* has included modules to enable definitions of various fire impact models, heat transfer analyses on structural members, and large-scale structural analyses using thermo-mechanical structural models [48, 49, 91]. While modelling timber structures in fire

well represents the need for integrated simulation of fire impact and structural response, OpenSees for fire as a research testbed is a suitable platform deployed for this task.

3.2.1 Software framework of OpenSees for fire

The software framework of OpenSees for fire is shown in Fig. 3.1, which mainly consists of two modules, i.e., the Heat Transfer module, and the thermo-mechanical analysis module. Following the object-oriented architecture of the original OpenSees, the codes for modelling structures in fire are distributed in a number of classes. In the heat transfer module, a mesh tool is offered to discretise an entity into HT_nodes and HT_elements with HT_materials for thermal properties and HT_BC for thermal boundary conditions (ambient, fire exposure), which are stored in the HT_domain and analysed using HT_analysis classes. Similarly, a thermo-mechanical analysis is supported by a domain comprising thermo-mechanical versions of materials (uniaxial, nD), sections, and elements (beamcolumn, shell, joint, etc.) as well as the ThermalAction for defining temperature histories. To run the analysis, interpreters are enabled to accept Tcl or Python scripts, which convert the scripts to the C++ functions of OpenSees for fire.

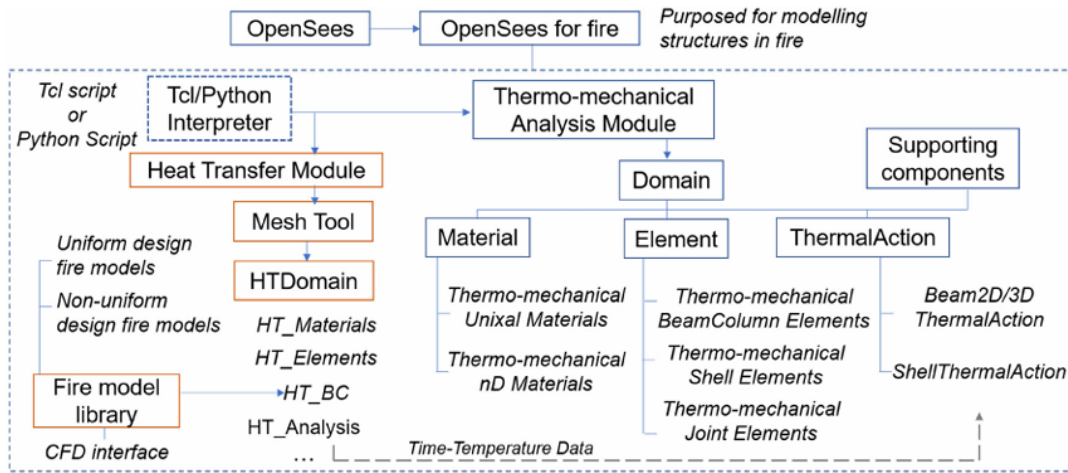


Fig. 3.1. Software framework of OpenSees for fire.

3.2.2 Extending OpenSees for modelling timber structures in fire

OpenSees for fire has been previously developed and used for modelling steel structures and reinforced concrete structures. For modelling timber structures in fire, the development should account for (1) the appropriate fire models to describe real fire impact to timber members; (2) suitable heat transfer models to predict the temperature evolution responding to various fire scenarios; (3) different thermo-mechanical models for timber beams, columns, and slabs and the consideration of charring. Fire models representing the increased fire impact due to the burning to timber components should be brought to the modelling framework. Heat-flux based fire models may be used as engineering models and CFD fire models could provide more details of fire loading, as illustrated in Fig. 3.2. When the fire impact is applied on timber sections, heat transfer analyses are performed to estimate the temperature evolution across the timber

sections. The internal heat generated by the timber burning in the form of flaming and smouldering should be addressed during the propagation of charring from one or multiple sides. The time-variant temperature profiles of timber sections are defined as thermal action, which transfers the heat transfer results to thermal loading on thermo-mechanical elements in *OpenSees*. Take an example of modelling timber beams, a zone-based thermal action beam element is required to deal with three-side fire exposure, which allocates temperatures to fibres of a fibre-based section at each integration point of the thermo-mechanical beam-column element. These fibres are assigned with the developed thermo-mechanical material models for timber, which incorporates the temperature-based material degradation and strain-stress relationship into the material model. For slabs, shell sections of plate fibre materials are employed, which suits well the properties of laminated timber panels. Note that the modelling capabilities are limited to typical timber structural members, whereas the connections are not yet modelled.

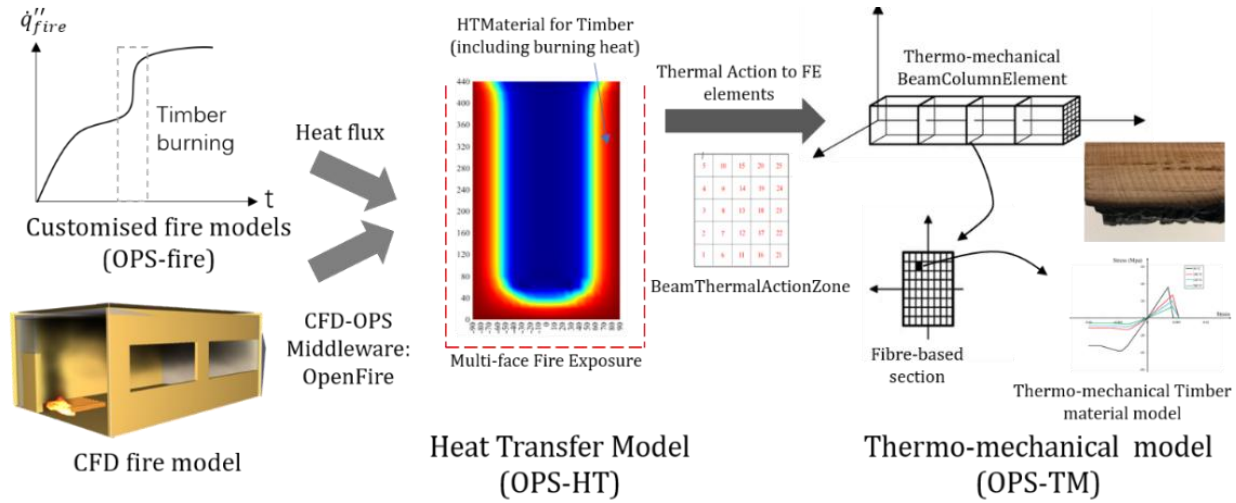


Fig. 3.2. Extending OpenSees for fire for modelling timber structures in fire.

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

Within the heat transfer module of OpenSees for fire, a layer-based heat transfer (HT) material model considering the timber combustion effect and layer transitions has been developed. The heat transfer model aims to predicting temperature evolution of mass timber sections [92] exposed to realistic fires [48] while recognising the key limitation of EC 5 model for standard fire exposure. Timber sections are represented using a heat transfer material of a layered formulation of temperature variant thermal properties, which co-works with a heat generation model to estimate the heat from timber combustion. When the timber sections are exposed to a fire, layer transitions occur from original wet wood to dry wood, and to char layer and ash layer if combustion sustains on its surface (Fig. 3.3a). The *OpenSees* *HTTimber* material model adopts a phase tag to record its layer state, which differs from the traditional solely temperature-variant thermal property model and enables the consideration of cooling and reheating on timber sections. For layer state transitions, the critical temperature from wet wood to dry wood is dominated by evaporation (100 °C),

while the drying process is distributed into a temperature range of 95 °C to 125 °C similar to the EC 5 model. When the temperature is higher than 200 °C, dry wood undergoes pyrolysis and then transfers to a char layer with the characteristic temperature of the front taken as 300 °C as a commonly accepted assumption [93]. During the charring process, the combustion heat of timber is largely released to the room environment as the burning of pyrolysis gas, whereas a small portion of this heat is absorbed by the timber section and transferred to the deeper layer, and this dominates the charring propagation in low-intensity fires. Therefore, the combustion heat model for the char layer proposed in the author's other work [92] based on Hopkin's model [66] is activated to consider the heat generation due to combustion.

It should be clarified that the layer-based heat transfer model terminology differs slightly between Chapter 2 and Chapter 3 due to the distinct publication contexts of the underlying studies, rather than any conceptual inconsistency. In Chapter 2, which corresponds to Work 1 (the heat transfer study under peer-review), the model description omitted the “ash layer” in response to reviewer comment. The charred zone was presented in broader terms without separating out the ash, to simplify the terminology as requested by the peer reviewers. In Chapter 3, corresponding to Work 2 (the subsequently published study), a more detailed layer stratification is retained. Here, the char layer is subdivided into a high-temperature combustion sub-layer (active charring zone) and a black char layer (inert char zone), and an ash layer at the exposed surface is explicitly defined. This finer distinction reflects the level of detail preserved in the published version of the model.

Facilitated by the layer state tag, the thermal properties of each layer of timber consisting of density ρ , specific heat C_p and thermal conductivity k (Fig. 3.3b) are defined based on the EC5 thermal property models¹ and data in [23, 25, 28, 70], as well as the consideration of heat generation due to timber combustion [66], which now is dominated by the material temperature and layer states. In the case that the layer transition does not occur, these thermal properties vary with elevated temperature and are linearly interpolated between the key control input parameters at ambient temperature, dry state (100 °C), and char state (300 °C). If layer transitions occurred and temperature falls back below the transition temperature, the interpolation for thermal properties will be suspended and the thermal properties along with the layer tag recording its state will remain the committed values. Hence, as the external net heat input decreases and cooling occurs, the layer properties would not incorrectly recur (e.g., a cooled char layer) as demonstrated in the parametric fire test with cooling (Fig. 3.3c). The application of the developed heat transfer model has been kept largely simple. A detailed description of the model and validation have been reported in chapter 2 focusing on the heat transfer model of timber [92]. It is noted that the thermal properties of various timber types are of high uncertainty, and the model parameters can be taken with reference to past experimental studies [23, 25, 28, 70, 94]. More fire tests on a variety of timber sections might be needed for quantifying the thermal property variables and this heat transfer model will be further refined in future studies.

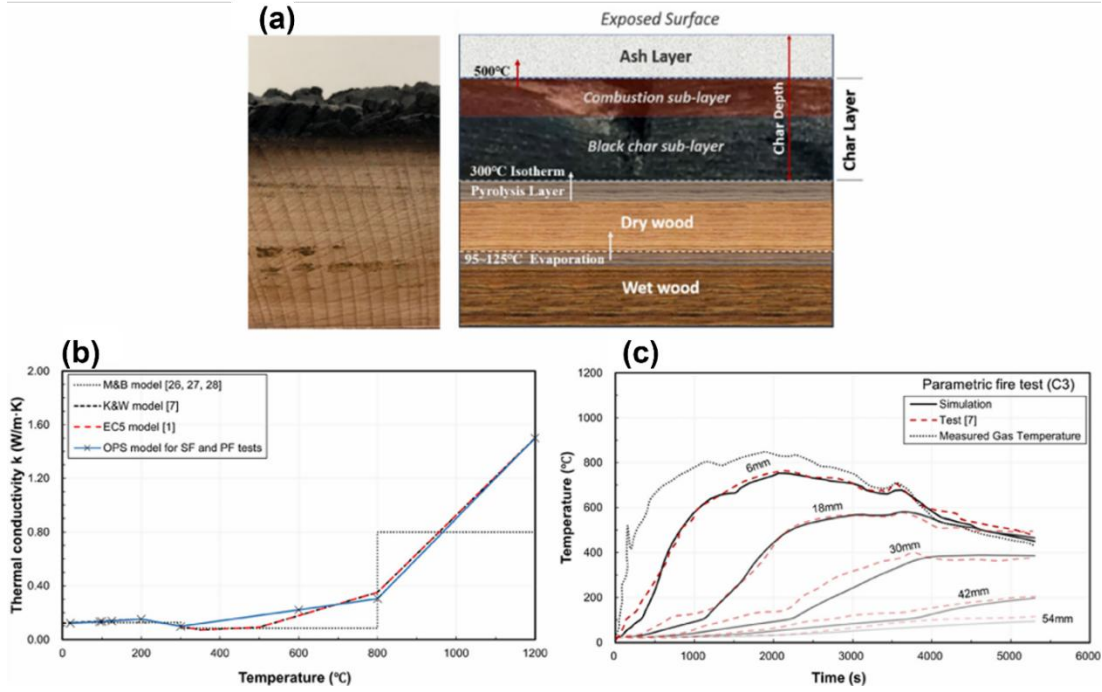


Fig. 3.3. A layer-based heat transfer model for timber exposed to fire: (a) Layers of timber section exposed to fire; (b) Thermal conductivity model of timber; (c) Modelling of parametric fire test (C3) specimen [25].

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

3.2.4.1. Constitutive model for timber

Timber is an anisotropic material of relatively complex material behaviour compared to concrete and steel since its tensile and compressive properties differ at different stress directions [95], which are usually described regarding directions parallel to the grain and perpendicular to grain (tangential behaviour may be also included if considering shear). The material properties perpendicular to grain are usually weaker than properties parallel to grain in terms of modulus of elasticity, tensile strength and compressive strength [96]. An engineering model of constitutive relationship for timber was proposed by Glos [97], which employed a non-linear constitutive model to define the stress-strain relationship under compression by means of four parameters: compressive strength f_c , elastic modulus, strain at maximum stress ϵ_c and asymptotic stresses $f_{c,end}$. While adopting an elastic-to-plastic relationship for compressive behaviour, an elastic-to-brittle behaviour was usually used for tensile behaviour [98-101]. Hence, the overall model for stress-strain relationship of timber material based on Glos's model is given as Eq. 3.1.

$$\sigma = \begin{cases} 0, & \epsilon > f_t/E_t \\ E\epsilon, & \epsilon > 0 \\ \frac{\epsilon + k_1\epsilon^7}{k_2 + k_3\epsilon + k_4\epsilon^7}, & \epsilon < 0 \end{cases} \quad (3.1)$$

where the coefficients k_1 , k_2 , k_3 and k_4 are constants related to the defined strain ε_0 corresponding to the ultimate compressive stress ($f_{c,0}$), the modulus of elasticity E . The detailed definitions of these coefficients can be referred to the literature [102]. Based on Glos' model, Hartnack [102] linearised the curves proposed by Glos into multiple segments as shown in Fig. 3.4, where the specific points for linear interpolation are listed in Table 3.1. This model has been adopted in *OpenSees* as the material models of timber at ambient temperature. It should be noted that a rapid decline of tensile stress is defined within a small strain range (e.g., 0.001) after the timber reaches its ultimate tensile strength depending on the individual, which is for the concern of computational convergence.

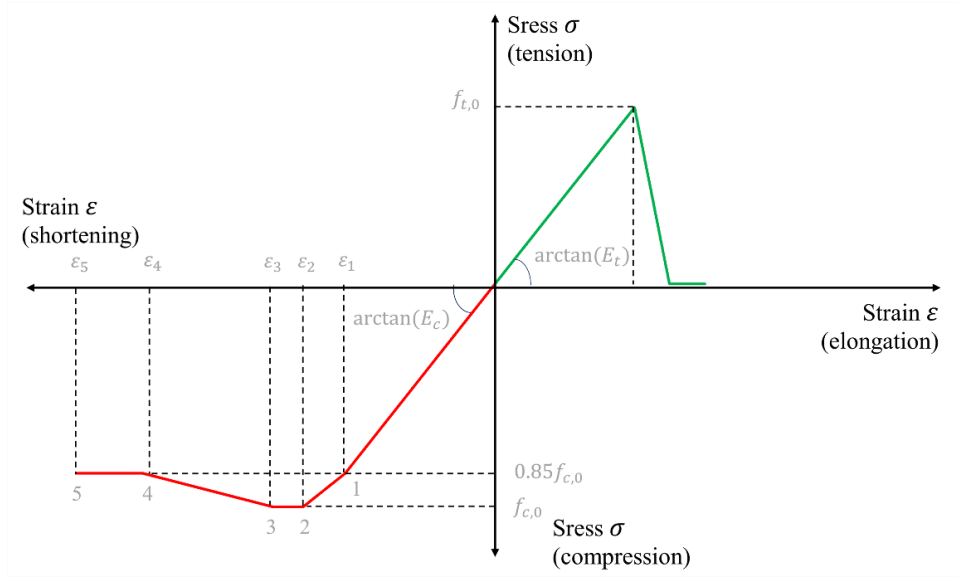


Fig. 3.4. Stress-strain diagram of timber according to the constitutive model [97].

Table 3.1. Linearization of the compressive zone of the constitutive curve for timber [102].

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	$\varepsilon_5 = 0.01$	$\sigma_5 = 0.85 \times f_{c,0}$

This constitutive model for timber is to describe the material behaviour of timber fibres under compression or tension along the direction parallel to grain. According to the experimental and numerical work conducted by Fragiaco et al. [34], the strength perpendicular to grain can usually be defined as 1/10 of the strength parallel to grain, where the modulus of elasticity perpendicular to grain is usually less

than 1/100 of that parallel to grain. For timber beams of engineered timber sections such as Glulam, the load bearing capacity is apparently dominated by the fibres along the grain direction and the shear transfer between fibres, which is currently assumed to be perfect bound. In the analysis of cross-laminated timber members such as CLT slabs, the strength and modulus of elasticity perpendicular to grain can be modelled using the timber material model with reduced model parameters as mentioned while adopting the layer-based section description.

3.2.4.2. Mechanical properties of timber at elevated temperature

The mechanical properties of timber are significantly affected by elevated temperature featuring the zero-strength layer after charring. The mechanical performance of timber sections remains approximately constant before drying, and material degradation occurs after it. When the pyrolysis completes and the timber turns to a char layer, the load-bearing capacity of timber members rapidly reduces, resulting from the charring propagation [57, 86]. Hence, estimation of the char front and modelling of mechanical properties of timber fibres before charring become the key components of evaluating the fire performance of timber structural members. In EC 5 [8], the compressive strength, tensile strength, and modulus of elasticity (tension and compression) at elevated temperature parallel to grain are expressed as temperature-related variables $f_{c,T}$, $f_{t,T}$, $E_{neg,T}$ and $E_{pos,T}$, respectively. As shown in Fig. 3.5, the reduction factors corresponding to these variables change linearly from 1.0 to different values at 100°C representing the drying effect on timber properties. From 100 to 300 °C, the mechanical properties of timber continue to decrease as timber undergoes pyrolysis. Although timber temperature reaches 300 °C and above, the mechanical properties are deemed as zero resulting from charring. Moreover, the maximum temperature is recorded in the thermo-mechanical material model, which co-works with the heat transfer model to prevent backward state change of timber layers when temperature declines. It should be noted that these EC5 suggested reduction factors for the mechanical properties at elevated temperatures may bear the limitations induced by the limited test data and the linear interpolation imposed.

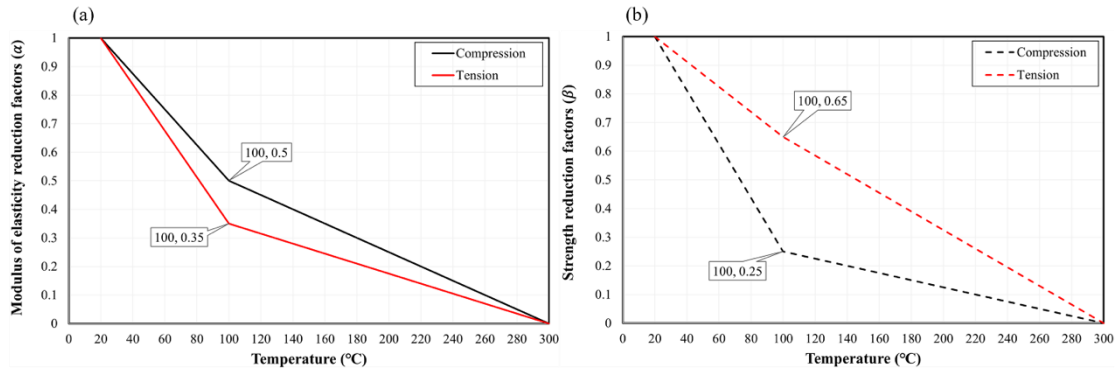


Fig. 3.5. Reduction factors for timber material properties at elevated temperature: (a) Elastic modulus for compression and tension; (b) Compressive strength and tensile strength.

3.2.4.3. Zone-based thermal action for timber beams

Transferring temperature data from *OpenSees* heat transfer module to thermo-mechanical elements requires the use of thermal action. For timber structural members especially timber beams and columns with multiple sides of fire exposure, zone-based thermal action is employed. This particular thermal action (*BeamThermalAction3D*) has been developed and implemented for applying fire induced temperature profile to timber structural elements. When using it, an external data file is generated upon the completion of heat transfer analyses on timber sections exposed to a fire. The data file consists of time steps and the corresponding 35 values for defining the zone-based thermal action, which include 5 coordinates each along the local y and z axes (y-loc and z-loc) of the timber section formulating a 5×5 grid with temperature data as shown in Fig. 3.6. Considering that only non-charring section is of interest, the given values of y-loc and z-loc are adaptive to the char front. Particularly, the timber fibres out of the grid will be assigned with the corner temperature of over 300 °C. Within each cell of the grid, the interpolation for determining fiber temperature can be performed automatically with a function of *flag*: *genInterpolation*. The interpolation scheme in each cell is given as Eq. 3.2, where the individual parameters are shown in Fig. 3.6c:

$$\begin{cases} T_{zi-1} = T_{(i+5*j-6)} + \left(\frac{fiberLoc_y - y_{i-1}}{y_i - y_{i-1}} \right) \times (T_{(i+5*j-1)} - T_{(i+5*j-6)}) \\ T_{zi} = T_{(i+5*j-5)} + \left(\frac{fiberLoc_y - y_{i-1}}{y_i - y_{i-1}} \right) \times (T_{(i+5*j-5)} - T_{(i+5*j)}) \\ T_{fiber} = T_{zi-1} + \left(\frac{fiberLoc_z - z_{i-1}}{z_i - z_{i-1}} \right) (T_{zi} - T_{zi-1}) \end{cases} \quad (3.2)$$

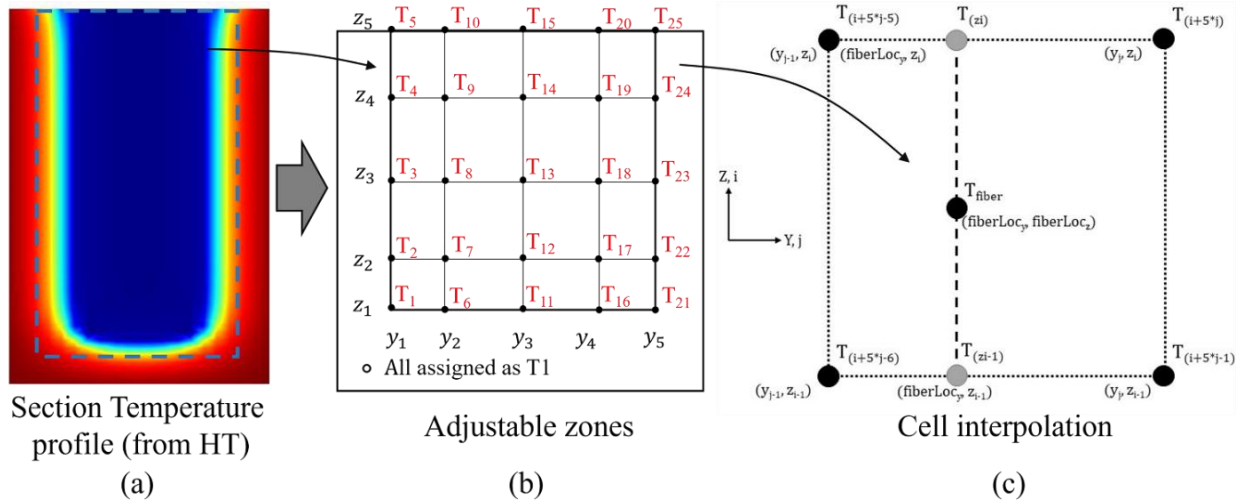


Fig. 3.6. Zone-based thermal action definition for timber beams in OpenSees for fire: (a)

Temperature profile of timber beam with 3-side fire exposure; (b) Zone-based thermal action; (c) Cell interpolation for timber fibre temperature.

3.2.4.4. Modelling procedure in OpenSees for fire for timber members in fire

With the developed components in *OpenSees*, modelling timber structural members in fire is now enabled and can be carried out following the workflow as shown in Fig. 3.7 in a loosely coupled form. Currently, the Tcl interpreter as a default choice is employed to interpret the input script to modelling procedures of *OpenSees*. For typical thermo-mechanical analyses, the script begins with specifying the model type as a 2D model or a 3D model. Nodes, materials (e.g., timber material), sections, and elements are then routinely defined to build a model of a single structural member, an assembly, or a whole structure. Prior to performing ambient loading and thermo-mechanical analyses, the output request should be given for monitoring nodal variables and elemental variables. The mechanical load representing the gravity load and service load at ambient condition is applied and analysed first. For modelling the fire induced behaviour of timber structural components, the thermal action definition is defined using *BeamThermalAction3D* or *ShellThermalAction* for beams and slabs, respectively. To obtain the time-variant temperature profile of timber sections exposed to fires, heat transfer analyses are conducted along with the definition of *HTEntity*, *TimberHTmaterial*, and fire models. Facilitated by the open-source and module-based *OpenSees* framework, further development involving more capabilities and models for simulating timber structures will be continuously conducted and the development from fellow researchers are welcome.

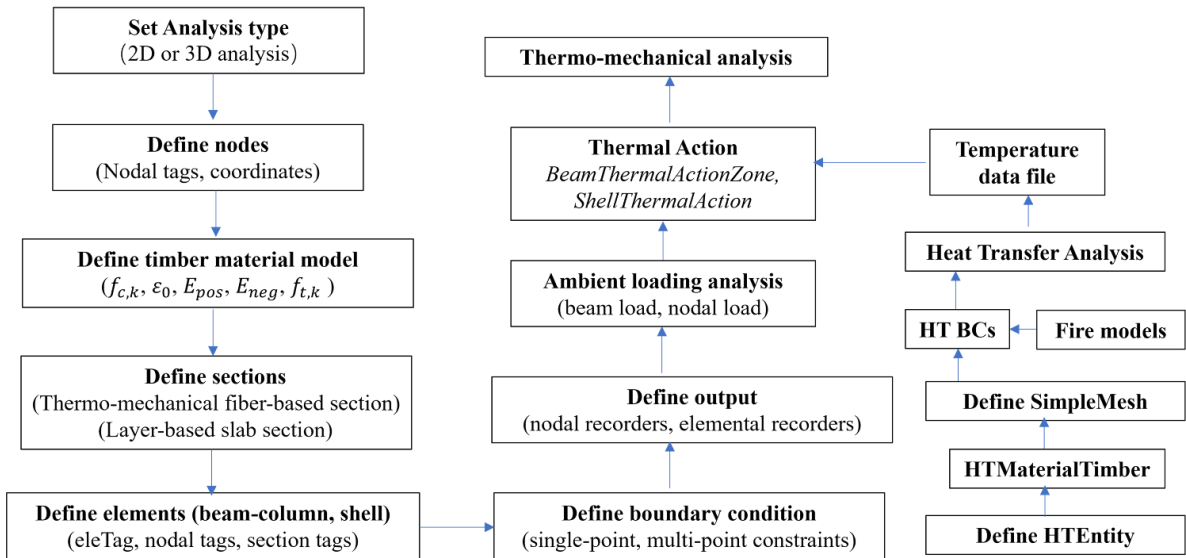


Fig. 3.7. Workflow of modelling timber structural members exposed to fire in *OpenSees* framework.

A simple verification case for thermo-mechanical model of timber section in fire is conducted. This model comprises a single *DispBeamColumn2DThermal* element representing a 50 mm long mini-beam, which is of a 25 mm×25 mm square-shaped cross section (Fig. 3.8). The section is described using *FibreBeamSection2D*, which is discretised into 25 fibres along with the timber material model. The material

properties of timber are defined as shown in Table 3.2, where the tensile strength of timber parallel to grain at ambient temperature is 41.77 MPa, corresponding to a strain of 0.00300. The compressive strength represented by peak compressive stress is -52.74 MPa, corresponding to a strain of -0.00457. The elastic modulus of timber fibre is 12564 MPa. By running this simple verification model, the stress-strain variation curves of timber are obtained by applying axially tensile load and compressive load. Fig. 3.9 shows the uniaxial material behaviour at 25 °C and the stress-strain curves at elevated temperatures of 50 °C, 100 °C, 150 °C, and 200 °C. When increasing the fibre temperature, the material degradation of timber fibres as shown in Fig. 3.9 exhibit the same variations as defined in Eurocode 5 [8].

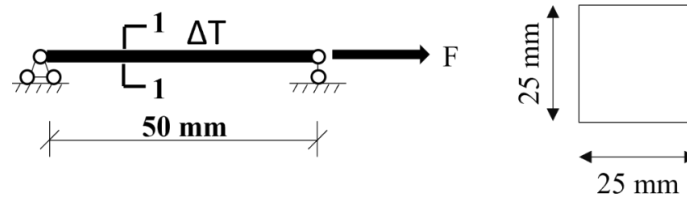


Fig. 3.8. A simple verification case for thermos-mechanical model of timber in fire.

Table 3.2. Material properties adopted in the modelling [34].

Elastic modulus (MPa)	Tensile strength (MPa)	Compressive strength (MPa)	Poisson's ratio
12564	41.79	52.74	0.30

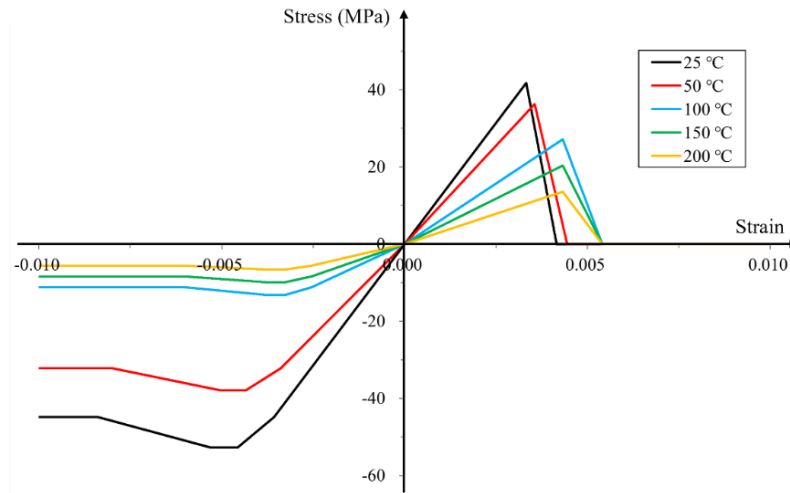


Fig. 3.9. Stress-strain curves simulation results for timber at different high temperatures.

3.3 Modelling fire resistance of timber members exposed to fires

3.3.1 Modelling CLT timber panel tests at ambient temperature and under fire exposure

CLT as an engineered timber product has been widely used in modern timber structures, which is of typical layer-based formulation allowing section models using fibres or layered fibres. Fragiacomano et al.

[34] performed multiple tests on CLT panels, which were 5600 mm × 600 mm × 150 mm. The CLT section comprised five layers and the thicknesses were 42 mm (L), 19 mm (T), 28 mm (L), 19 mm (T), and 42 mm (L), while L indicates longitudinal direction parallel to grain and T represents transverse direction. One CLT panel was tested with two-point loading at ambient temperature, whilst another one was tested with a uniformly distributed load of 6 kN/m and furnace heating at the bottom surface as shown in Fig. 3.10. The mid-span deflection of the beam was measured in both tests, and the temperatures were monitored in the furnace fire test using thermocouples at various depths of 21 mm, 52 mm, and 75 mm from the bottom. The furnace temperature of the fire test was prescribed following ISO834 fire curve [15], which was terminated at the failure point of the CLT beam. During the fire test, the side surfaces of the specimen was insulated and fixed by the protective layers of gypsum plasterboard, which was to approximate 1D heat transfer from fire to timber section. The CLT layers were made of spruce of C24 strength grade and the average density of the tested CLT at ambient temperature was 452 kg/m³. In terms of mechanical properties, the ultimate tensile strength and compressive strength parallel to grain were 41.79 MPa and 52.74 MPa, respectively. The modulus of elasticity and Poisson's ratio were suggested as 12564 MPa and 0.30. On the direction perpendicular to grain (transverse direction), the ultimate tensile strength and the ultimate compressive strength were suggested to be 4.2 MPa, 5.3 MPa. Correspondingly, the elastic modulus along transverse direction can be adopted as 120 MPa.

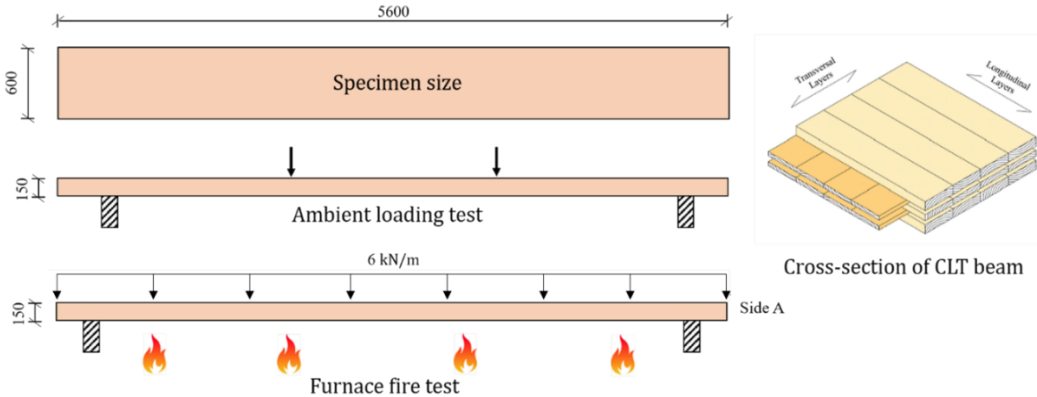


Fig. 3.10. CLT beam test at ambient temperature and under furnace fire, adapted from [34].

3.3.1.1. Simulation of static loading behaviour at ambient temperature

Based on the aforementioned development in OpenSees for fire, the tested CLT beams can be modelled using either a beam element model or a shell element model. The former employs displacement-based thermo-mechanical beam-column elements and fibre-based beam sections. The cross laminated layers can thereafter be discretised as fibres of different timber material to represent longitudinal layers and transverse layers. When using shell elements, thermo-mechanical shell elements (*ShellMITC4Thermal* or *ShellNLDKGQThermal*) can be used, which are desirable to describe the behaviour of CLT slabs of two-

way mechanism. Both approaches are used to model the static loading behaviour of this CLT beam at ambient temperature. Along the beam length direction, 40 elements are sufficient to describe the bending behaviour according to previous study. Along the depth of CLT section, each layer is defined with 5 or 10 fibres of evenly distributed fibre area in the thin or thick layer. The material models (*TimberECThermal*) using the above-mentioned mechanical properties are assigned to these fibres differed by the layer grain direction. For shell element model, the section defined using *LayerShellSectionThermal* comprises multiple layers of plate fibre type material (15 layers used in this model). The multi-dimensional material uses a wrapper section (previously developed *PlateRebarThermal*) which transfers a uniaxial material to a layer material for shell section. Ideally, a specific plate fibre material for timber should be developed for modelling the two-way load bearing mechanism of CLT slabs. Nonetheless, the current model ignoring in-plane shear action at each layer (two-way effect) is suitable for modelling the CLT beams.

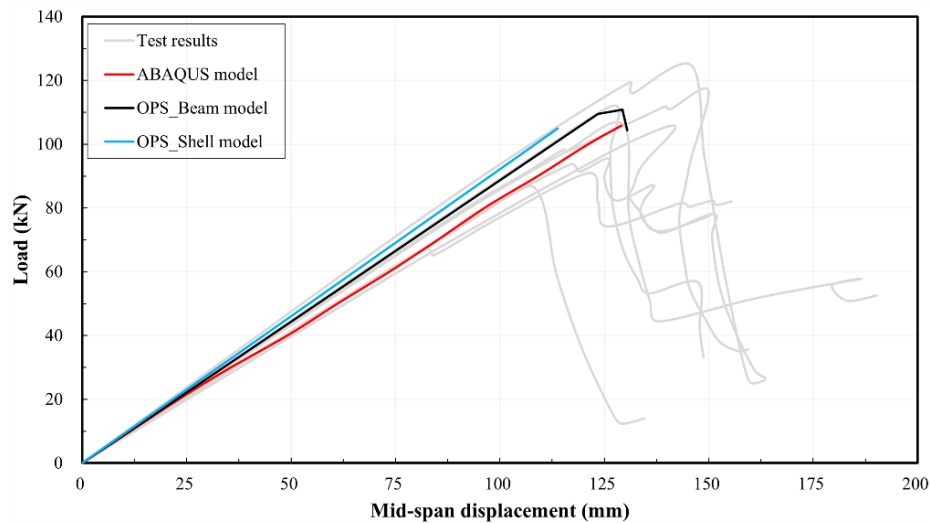


Fig. 3.11. Load-displacement curves obtained from CLT beam tests [34] at ambient temperature and modelling results.

When imposing a two-point load on the beam, the mid-span deflections of the eight CLT beams measured in the ambient loading tests were measured and shown in Fig. 3.11. Prior to failure indicated by rapid decline of load, the behaviours of CLT beam specimens are considerably similar but of different slopes of load-displacement curves. The numerical attempt by Fragiacomio et al. [34] using an ABAQUS model was included in Fig. 3.11 as well. In the same figure, the modelling results from the beam element model and the shell element model of *OpenSees* were illustrated, which are both able to show the very similar behaviour before the failure. Unlike the ABAQUS model without presenting the decline, the OpenSees beam model is able to show the failure of CLT beam using an arc length integrator. The simulated failure point at the ultimate load of 110 kN perfectly overlaps a curve of measured data among the test series.

3.3.1.2. Modelling heat transfer of CLT panel

A 2D heat transfer model was created for modelling the fire impact towards the CLT beam using the OpenSees HT module and the layer-based HT material for timber. The CLT section along the depth is meshed as 1 mm for each element. On the fire-exposed surface, the convective heat transfer coefficient (h) is set as 25 W/m²K, while a coefficient of 4 W/m²K is assumed for the unexposed surface as recommended by Eurocode 1 [56]. The emissivity of the timber surface is 0.8 for radiation. For the heat transfer material model, and the key material parameters adopted by Xing et al. [90] were used. Considering the CLT beam is subjected to standard fire exposure, the EC 5 model is applicable and the results of using EC 5 model are given as comparison.

As shown in Fig. 3.12a, the time-variant temperatures at the depths corresponding to installed thermocouples are illustrated. The various curves represent the test data, the results from EC 5 model and the results from the developed heat transfer model of *OpenSees*. Note that the new model is purposed to model timber sections subjected to non-standard fire scenarios, here both EC 5 model and the new model are able to predict the temperature evolution. It is seen that the timber at 21 mm deep from the exposed surface increased rapidly after 1800s, whereas the deeper section at 75 mm remains cool throughout the test. Taking advantage of the layer state tags provided by the new model, the layer transitions in the timber section can be depicted as shown in Fig. 3.12b, which shows the distributions of wet wood, dry wood, char layer, and ash layer at 1200s, 2400s, 3600s, 4800s and 6000s throughout the test. From Fig. 3.12a, the test data at 52 mm after 4800s is higher than the simulated values, which may be due to the load induced effect and the model errors in terms of thermal properties. During the test, Fragiacomio et al. [34] reported that the specimen experienced larger deflection than the adjacent panels for insulation, which created a gap allowing the furnace fire being imposed on both sides of the panels. Furthermore, the delamination of CLT layers during fire tests have not been considered neither in the universal EC 5 model nor the advanced heat transfer model considering combustion heat. This effect should be addressed in future investigations and should be considered more appropriately in the numerical analysis models.

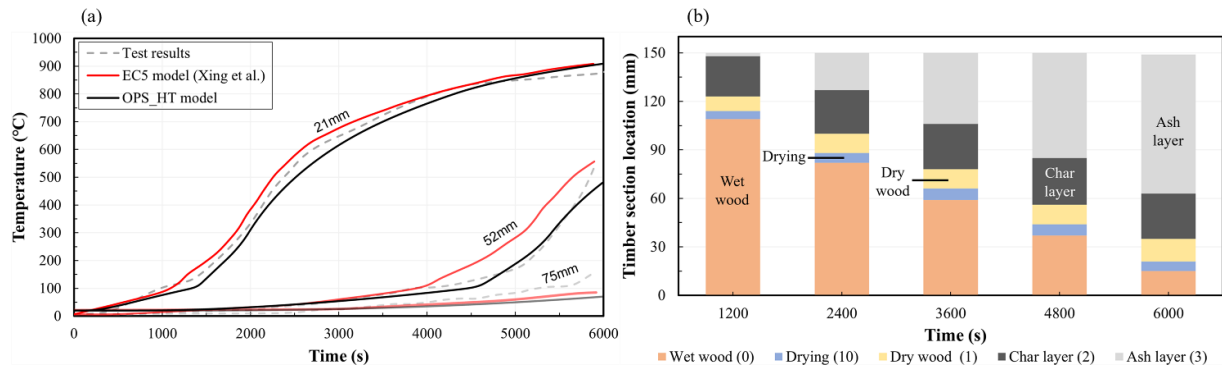


Fig. 3.13. Thermal response of S1 specimen [34] of the standard fire: (a) Temperature evolution; (b) Charring depth history.

3.3.1.3. Modelling thermo-mechanical behaviour of CLT panel

With the obtained temperature history data from heat transfer analysis, the models of CLT panel built with beam elements and shell elements can be used to analyse the thermo-mechanical behaviour. As the temperature evolution across the CLT section is one dimensional (1D), a 9-point thermal action is sufficient for beam sections and shell sections in the corresponding models. The thermo-mechanical model of this CLT beam is identically configured as the model for ambient loading test. The mid-span deflection of the CLT beam obtained from the test and the modelling results retrieved from various models are illustrated in Fig. 3.13. The simulation results presented by Fragiacommo et al. [34] using ABAQUS are included for comparison. As shown in the figure, both the OpenSees beam model (OPS_Beam) and the OpenSees Shell model (OPS_Shell) are able to predict the behaviour accurately in the first 70 min, but closer results were given by the ABAQUS model after 70 min. Similar to the ambient loading behaviour, the shell model predicts slightly lower deflections in the beam as it consists of 15 layers compared to the 25 fibres of the beam section across the depth. In the late stage of the fire test, the beam deflection increased faster than the curve of simulation results. This may be due to the reported fire flames on beam sides after the large deflection around 80 min and the CLT beam was subjected to more section loss leading to the eventual failure after 99 min. When introducing linearly increased gas temperatures at both sides of the beam in the heat transfer analysis to represent this effect, i.e., 20 °C-200 °C from 60 min to 80 min, and 200 °C to 800 °C from 80 min to 99 min, the OPS_Beam model (considering side fire exposure) successfully reproduces the beam failure. This is indicated by a run-away failure and the convergence.

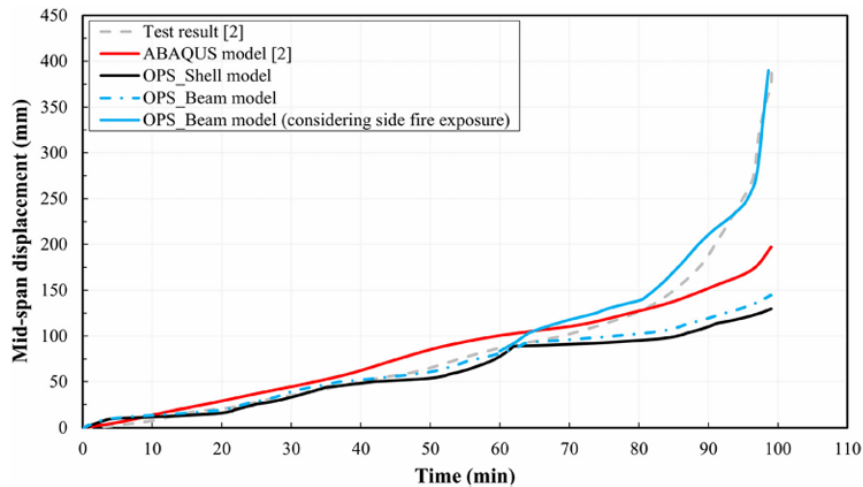


Fig. 3.13. Experimental and numerical displacement of S1 specimen [34] exposed to the standard fire.

3.3.2 Modelling of a glulam beam of three-side fire exposure

Timber beams have been used in floor systems of timber buildings, which are key components to support various forms of slabs made of concrete or timber and are usually subjected to three-side fire exposure. A glued laminated timber beam of 3500 mm × 180 mm × 440 mm was tested by Dârmon and

Lalu [85], which was 3.5 m long and simply supported. A furnace following a standard fire curve development was employed to impose fire exposure on the Glulam beam, excluding the top surface that was insulated. During the test, the beam was subjected to a uniformly distributed load of 6.1 kN/m on its top surface. The strength class of this glued laminated timber beam was GL24H, while the dry density and moisture content were measured as 338 kg/m³ and 11.6 %, respectively. The tensile strength and the compressive strength were 19.2 MPa and 24.0 MPa, and the elastic modulus was 11500 MPa [103].

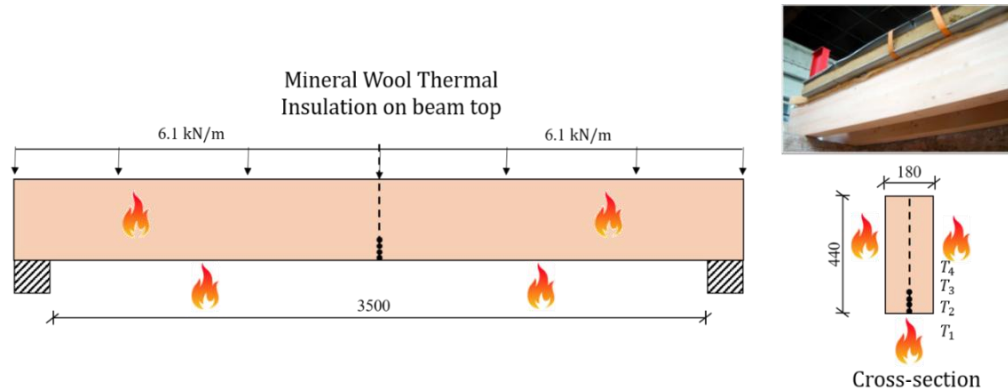


Fig. 3.14. A Glulam timber beam subjected to three-side fire exposure, adapted from [85].

3.3.2.1. Heat transfer simulation during standard fire

A 2D heat transfer model is exploited to model the Glulam beam of three sides exposed to standard fire. The cross-section was meshed along the width and thickness directions using a mesh size of 4.5 mm × 1.0 mm. As the timber type used in this test is similar to the CLT panel, the heat transfer material properties except the density and moisture content are kept the same, and the thermal boundary conditions and coefficients are also similarly defined. As shown in Fig. 3.14, thermal couples were installed on the specimen at mid-span, which were located at 10 mm, 20 mm, 40 mm, and 60 mm from the bottom surface and along the centre line of cross section. The temperature variations at these monitored points are plotted in Fig. 3.15a, which include the test data and the simulated results using SAFIR both reported by Dârmon and Lalu [85], as well as the results extracted from OpenSees HT models. The traditional EC 5 material model and the newly developed Timber HT material were used separately. Discrepancies exist between all the simulation results and the experimental data, while the EC 5 model leads to the largest discrepancies at the depth of 40 mm. The performance of layer-based heat transfer model is better but predicting lower temperatures at 10 mm in the first 20 minute, when comparing with the SAFIR analysis results. In general, the heat transfer model considering timber combustion does not significantly improve the prediction performance as this effect is minor in the case of furnace fire. The contour plots of temperature distribution in the beam section are presented in Fig. 3.15b, which clearly illustrates the fire impact on three sides of the beam. While the peak temperature in the ash layer reaches 800 ~ 900 °C, the transitions from wet wood or dry wood to char layer are limited to a narrow area. Similar to the challenge of modelling other loaded

timber members, the shrinkage of char layer and delamination of glued laminar may cause the accelerated propagation of charring and these effects are currently difficult to predict by the present heat transfer models. Nevertheless, subsequent sensitivity tests showed that refining the mesh resolution and reducing the simulation time step could further improve the accuracy of temperature evolution predictions. Future model extensions that incorporate timber cracking and post-char delamination are expected to better reproduce the complex heat transfer behaviour observed in real fire tests.

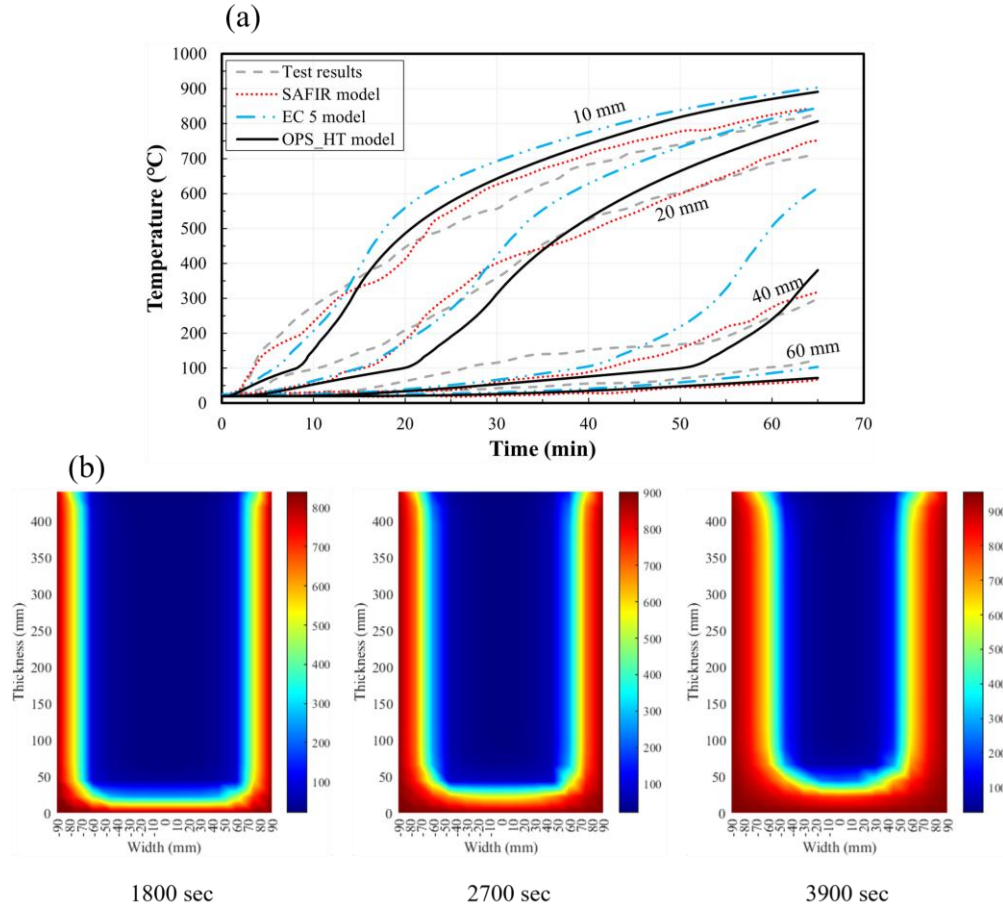


Fig. 3.15. Modelling Glulam beam [85] exposed to standard fire on three sides: (a) Comparison to test data [85]; (b) Modelled temperature profiles at 1800 s, 2700 s and 3900 s.

3.3.2.2. Thermo-mechanical analysis of glulam beam

The Glulam beam is modelled using beam elements of *DispBeamColumn3DThermal* type, which receives the zone-based thermal action to apply temperature histories due to three-side fire exposure. The cross-section of the beam is modelling using a fibre-based beam section of 20×20 fibres, along with the associated timber material model. The mid-span deflections of the beam obtained from various sources are shown in Fig. 3.16, which includes the test data and modelling results predicted by OpenSees model and SAFIR model. The test data and SAFIR model were both provided by Dârmon and Lalu [85], which are compared to the results from different OpenSees models employing 5, 10 and 35 elements. As found before

[104], the thermo-mechanical beam-column elements are of acceptable performance by using a few elements, even a five-element model. Comparing with the test data, both the SAFIR and OpenSees models present discrepancies on the mid-span deflections. Generally, the deflection development is better captured by the OpenSees model, which shows a similar slope of the deflection curve compared to the test from 25 min to 55 min. The predicted curve intersects with the test data at 62 min near the test end, but exhibiting a higher displacement rate indicating the approaching of beam failure. However, the mid-span deflection of this 3.5 m Glulam beam remained small even after one hour of fire exposure, which was around 4 mm. With respect to the modelling, a Glulam beam heated by fire on multiple sides is of more challenges as the Glulam section experienced debonding and delamination of timber laminar when exposed to three-side heating. Moreover, the performance of thermo-mechanical model depends on the heat transfer modelling accuracy and the resolution of thermal action. The uncertainty induced by timber material properties could be another source of error, which requires more test input to calibrate the model setup, especially in the context of realistic fire responses. Further analyses using refined temperature distributions, boundary conditions adjusted to reflect experimental support restraints, and inclusion of material variability demonstrated improved agreement with test results. While adopting the 5 % elastic modulus $E_{0.05}$ led to slightly lower predicted stiffness, this conservative assumption aligns with engineering design safety margins and remains appropriate for structural fire assessment.

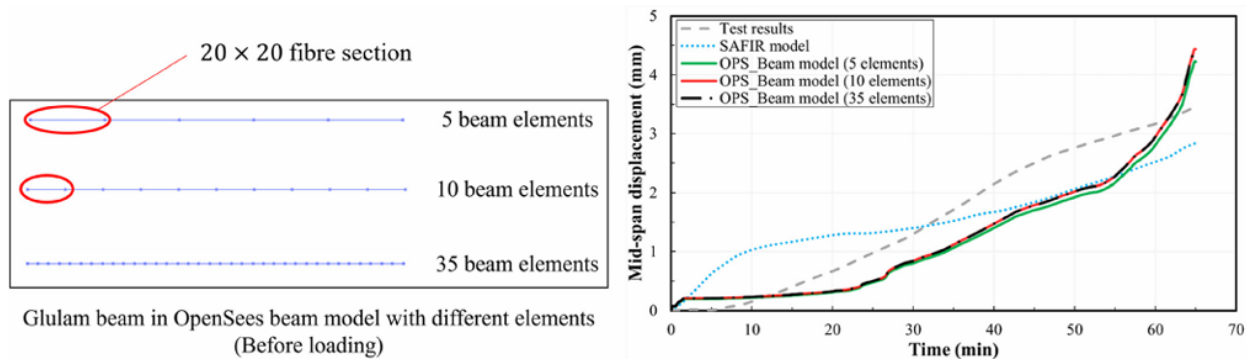


Fig. 3.16. Mid-span deflection of Glulam beam subjected to fire on three sides.

3.3.2.3. Further explorations for improving the prediction accuracy

To address the observed discrepancies between simulation results and experimental data in the three-side fire exposure beam case, several refinements were explored to improve the predictive accuracy of both the heat transfer and thermomechanical models.

In the heat transfer analysis, the initial models, using both the EC 5 and the newly developed Timber HT material, showed deviations, particularly in capturing the rapid temperature rise near the exposed surfaces and the charring progression, as shown in Fig. 3.17. Nevertheless, subsequent sensitivity tests showed that refining the mesh resolution and reducing the simulation time step could further improve the

accuracy of temperature evolution predictions. A finer mesh, especially near the exposed boundaries and expected char fronts, allows for a more precise representation of steep thermal gradients. Similarly, a reduced time step improves the stability and accuracy of the transient heat transfer solution, particularly during the initial phase of fire exposure when temperature changes are most rapid. These numerical refinements help better capture the early-stage temperature development, such as that observed at 10 mm depth within the first 20 minutes. Future model extensions that incorporate timber cracking and post-char delamination are expected to better reproduce the complex heat transfer behaviour observed in real fire tests. Such physical phenomena, which are currently not explicitly modelled, can significantly influence the actual charring rate and in-depth temperature distribution by creating new pathways for heat penetration.

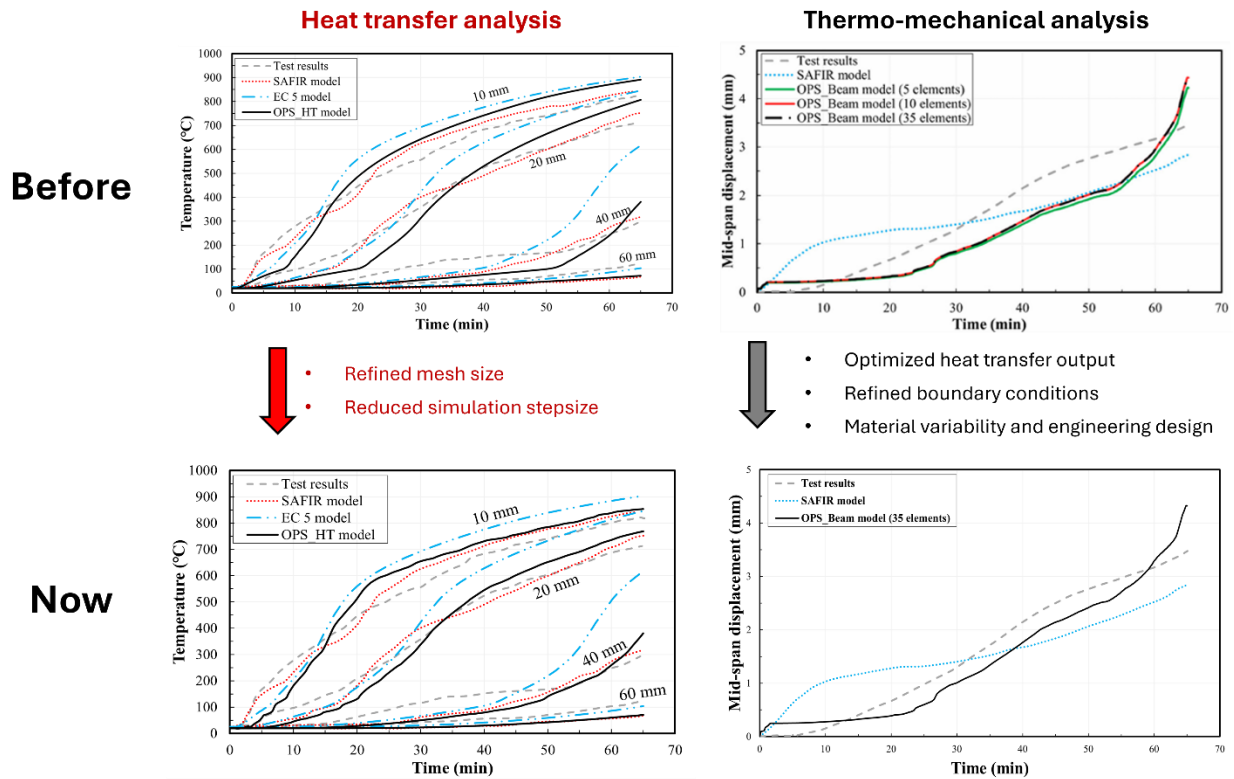


Fig. 3.17. Comparison of heat transfer analysis and thermo-mechanical analysis for Glulam beam with fire exposure on three sides before and after improvement.

For the thermomechanical analysis, the initial beam models demonstrated reasonable deflection trends but showed differences in stiffness and displacement rate compared to the test data. These discrepancies are attributed to several factors, including the simplified application of thermal loads, idealised boundary conditions, and the inherent variability of timber material properties. Further analyses using refined temperature distributions (obtained from the improved heat transfer models), boundary conditions adjusted to reflect experimental support restraints, and inclusion of material variability demonstrated improved agreement with test results. Specifically, adjusting the support conditions to more accurately represent the

partial rotational restraint present in the test setup helped align the simulated structural response more closely with the measured mid-span deflection. Regarding material properties, while adopting the 5% elastic modulus ($E_{0.05}$) led to slightly lower predicted stiffness compared to using mean values, this conservative assumption aligns with engineering design safety margins and remains appropriate for structural fire assessment. This choice acknowledges the natural variability of wood and ensures that the model predictions are not unconservative, which is critical for fire safety design.

In summary, while the current modelling framework provides a solid basis for simulating the fire behaviour of glulam beams, the accuracy can be enhanced through numerical refinements and a more nuanced representation of physical phenomena and boundary conditions. The ongoing development aims to integrate these improvements to achieve better predictive capability for complex fire scenarios, particularly those involving multi-sided exposure and the associated challenges of delamination and charring.

3.4 Application of simulation models for a composite member in realistic fire scenarios

Enabling modelling timber structures in fires in OpenSees platform is to address the essential need for integrated simulation to promote timber buildings with convincing fire safety performance. Although currently experimental tests were mostly limited on timber members using fire furnace following standard fire testing protocol, evaluating the fire performance of timber structures ideally requires the consideration of realistic fire development and system-level thermo-mechanical responses. This section presents a demonstration case study, which simulates a compartment fire considering the floor fire initiation and burning of timber components, followed by modelling the thermal and thermo-mechanical responses of the timber-concrete composite slab in this compartment analysed using OpenSees for fire. With this demonstration, the modelling routine for simulating timber structures in fire is illustrated, which is aimed for future implementation to provide fire performance evaluation towards more complex fire scenarios (e.g., non-uniform heating, cooling, and travelling fire behaviour) and more complicated structure systems (e.g., multi-storey building, steel timber-concrete composite structures)

3.4.1 Timber-concrete composite floor system in a compartment fire

In this case study, the compartment consists of a timber wall and a timber-concrete composite floor system, which is inspired by the experimental study by Hadden et al. [7] but of different configuration. The fire impact is simulated using a model in Fire Dynamics Simulator (FDS) [105], as shown in [Fig. 3.18a](#). Note that the fire simulation model remains preliminary and simplified for demonstration purposes, where four fire sources as initiation burners are defined to represent the wood crib used in the experiment. Nevertheless, the main task of the model is to generate a non-standard fire development history induced by the burning of floor fuel and timber components in the compartment (a CLT wall and a timber beam). The

model parameters for defining model geometry, timber wall, and floor fuel locations are adopted with reference to the tests. Note the test reported by Hadden [7] adopted a small size for the compartment design, which produces a nearly uniform upper zone. The mass loss rates of the floor wood block are prescribed using the test data given in the reference for Alpha test [7], which ignores the two-way effect between the wood crib and burning of timber components. Regarding the thermo-mechanical model, the timber-concrete composite (TCC) floor slab is modelled as a simply supported slab assembly, as shown in Fig. 3.18b. The plan size of the concrete slab is 2720 mm $\times$ 2720 mm $\times$ 100 mm, corresponding to the small compartment model. The size of the timber beam is 2720 mm $\times$ 200 mm $\times$ 200 mm.

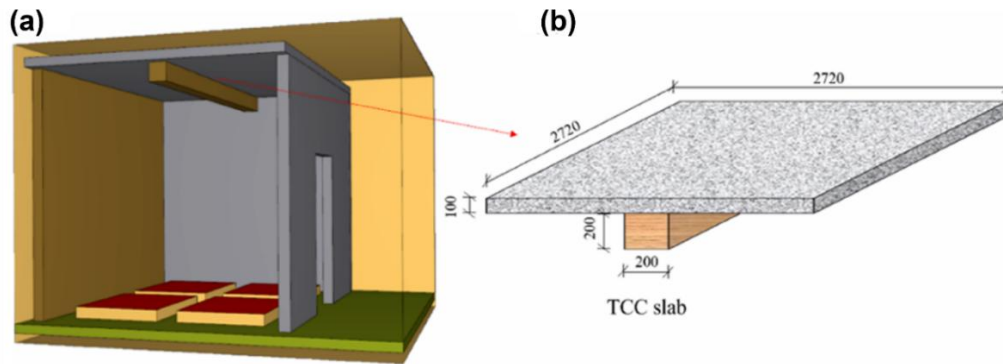


Fig. 3.18. Timber-concrete composite floor system subjected to a compartment fire.

The analysis presented in this section represents a preliminary demonstration of the CFD-OpenSees coupling for a timber-concrete composite (TCC) slab system. Several simplifications were adopted, including the assumption of homogeneous material properties, ideal rigid-link bonding between the timber beam and the concrete slab, and limited fire scenarios based on the generated non-standard fire curves. Although these curves provide more realistic boundary conditions than standard furnace tests, the simplified compartment configuration still differs from large modern open-plan spaces. Therefore, the present analysis should be regarded as an initial demonstration of feasibility rather than a comprehensive validation study.

3.4.2 Modelling thermal responses considering timber burning

The fire development in a timber building is significantly affected by the burning of timber components as they serve as additional fuel by producing pyrolysis gas. In this fire simulation model, localised fire flames are initiated at the wood blocks, and then the flames spread to the back timber wall (opposite to the door opening). The total mass loss rates of all combustibles and the prescribed mass loss rates of floor wood blocks have been plotted in Fig. 3.19a, which clearly shows the significant contribution of timber wall and beam to the fire development. In Fig. 3.19b, the time-variant gas-phase temperatures and adiabatic temperatures near the centre of the timber beam are illustrated, which are also compared to the standard fire curve. The cooling period of the room fire begins around 2040 s, marked by the end of the burning of timber wall and beam.

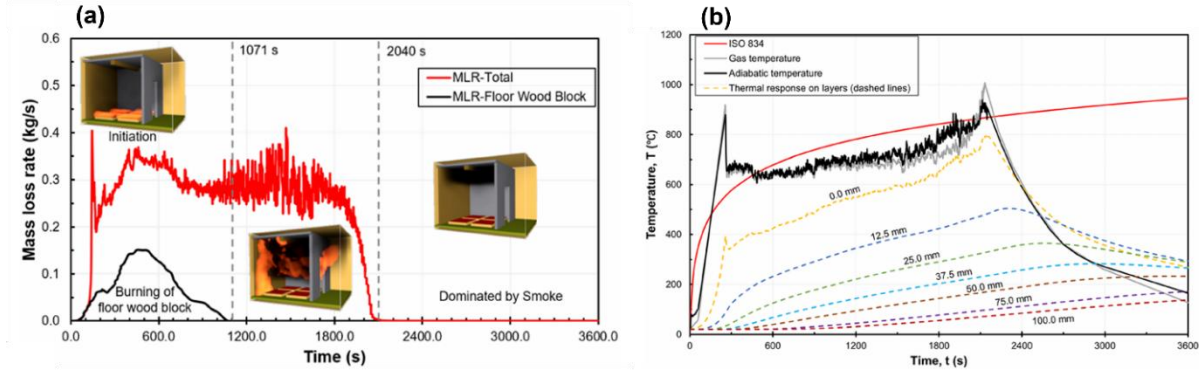


Fig. 3.19. Simulated fire action considering timber burning: (a) Mass loss rates; (b) Time-temperature curves at various depths of concrete slab section.

The simulated fire action is then applied to the heat transfer model of the timber beam underneath the concrete slab, which is defined using a *UserDefined* fire model of the obtained adiabatic temperature in OpenSees for fire [106]. The convective heat transfer coefficient and emissivity are adopted as those in the validation cases and the previous work [106]. The heat transfer material for the concrete section uses the previously developed *HTConcreteEC* [107], and the 2D layered heat transfer model for the Glulam beam is employed for the timber beam section. Considering the small size of the compartment, the fire action is assumed to be uniformly distributed near the ceiling and applied on the exposed surfaces. Upon the completion of HT analysis, the temperature histories at various depths across the slab have been shown in Fig. 3.19b, whereas the 2D temperature profiles of the three-face exposed timber beam are given in Fig. 3.20 with respect to different time steps of fire development. More than one third of the timber beam section has turned to char layer at 2875 s (gas temperature decreases to 300 °C), which presents charring propagation in the cooling stage compared to the section profile at 2149 s. Along with further cooling, the whole beam section starts to cool off. The use of layer state tags becomes important, otherwise these layers would be treated as original wood. This is equally important in defining the thermal action in thermo-mechanical analysis to deal with cooling, the calculated temperature histories are defined using the aforementioned *ShellThermalAction* and *BeamThermalAction3D*, while the charring of fibres is identified and recorded using the 300 °C isotherm.

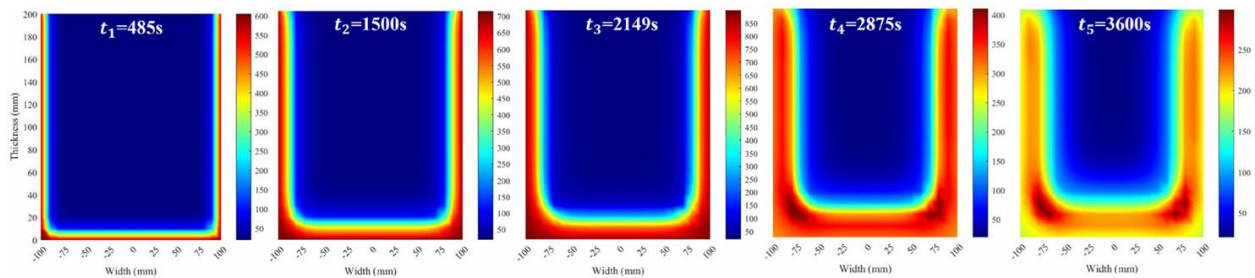


Fig. 3.19. Temperature profiles of timber section in the simulated timber building fire.

3.4.3 Thermo-mechanical responses of timber-concrete composite slab

The thermo-mechanical model is built with shell elements representing the concrete slab and beam elements for the timber beam, both subjected to fire action using the above-mentioned thermal action definitions. Regarding the concrete, the compressive strength is chosen as 20.88 MPa, while the tensile strength is 2.10 MPa and the elastic modulus is 12 528 MPa. A *ConcreteDamagePlasticity* developed by authors is used to model the concrete layers using layers. The yield strength of the steel rebar mesh in this concrete slab is 579.1 MPa, and the ultimate strength is 632.1 MPa, along with an elastic modulus of 210 GPa. For the timber beam, the density of timber is given as 548 kg/m³, the average moisture content is 12%, and its thermal and mechanical properties are similarly defined as the validation case of the Glulam beam. Between the concrete slab and timber beam, a perfect interfacial connection is assumed using rigid links in OpenSees. At ambient temperature, the ultimate load of this composite slab is obtained by means of a virtual loading test, which is found as 40 kN/ m² of UDL. When considering the fire impact, two cases are conducted using a UDL of 3.0 kN/m² and another UDL of 4.5 kN/m². The thermo-mechanical responses of this timber-concrete composite slab are shown in Fig. 3.20. While the load ratio is yet relatively low owing to the small slab size, the maximum central deflections of this composite slab are 23 and 26 mm under the UDL of 3.0 kN/m² and 4.5 kN/m², respectively. It is seen that the maximum deflection of this timber-concrete composite slab occurs at 43 min of the fire, which is 8 min after the start of cooling. It is then followed by a slow recovery of its displacement as the compartment cools off. For the case of 3.0 kN/m² of UDL, the stresses of timber fibres along the centreline of beam section at the middle-span of timber beam are monitored and illustrated. As shown in Fig. 3.20b, the stresses of timber fibres closer to the exposed surface are significantly influenced by the temperature evolution and the imposed load. For the fibre at 10 mm from the bottom surface, its stress reaches computationally zero very quickly as its temperature approaches 300 °C (charring) at the early stage. For the fibres at 40, 70 and 100 mm, they are under continuous tension and subjected to increased temperature, leading to tensile fracture of fibres and decline of stresses. Although the timber beam is subjected to bending, the neutral axis at mid-span section moves upward and the fibre stress at 150 mm experienced transition from compression to tension during the cooling stage. Meanwhile, the fibres at 180 mm and 200 mm remain under compression and the compressive stresses decrease as the cooled slab system recover from the deflection. Note that this demonstration case is to explore the responses of timber structures in a simulated small compartment fire, which demonstrates that the fire action to a load-bearing timber member can be significantly intensified by the burning of timber wall and beam. Moreover, fast propagation of tensile failure of timber fibres can be induced by the imposed load and temperature evolution, despite that the fibres have not fully entered charring. In future, it may be feasible to apply timber structures in a broader scope, as long as the fire safety

performance is assured with quantified indices. It certainly requires analysis tools to perform such integrated investigations, and the work presented in this chapter might be one of the fundamental steps

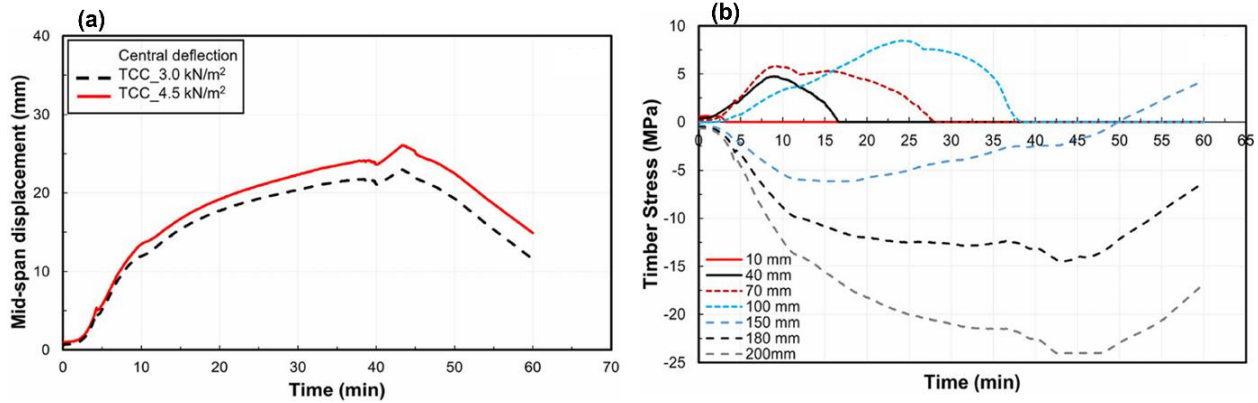


Fig. 3.20. Thermo-mechanical responses of timber-concrete composite slab: (a) Central deflection of the slab under different UDL; (b) Timber stresses at different locations of midspan section

3.5 Conclusions

In this chapter, the modelling capability for simulating timber structures in the fire of various aspects has been introduced to the *OpenSees* framework, which considers non-standard fire scenarios, implementation of timber heat transfer models, and thermomechanical analyses of timber beams and slabs. Taking advantage of the open source and object-oriented nature of *OpenSees*, a series of code development has been conducted, including: (1) timber heat transfer models considering combustion heat applicable to non-standard fire scenarios; (2) zone-based thermal action for timber beams of charring propagation on multiple surfaces; (3) a thermo-mechanical material model of timber to address the ambient behaviour and behaviour at elevated temperature. CLT beams tested at ambient temperature and using a fire furnace are modelled as validation, followed by simulation of a Glulam beam of three sides exposed to furnace fire. Despite some discrepancies due to model scope and the lack of material data, these analyses showed good performance in reproducing the temperature histories and the thermo-mechanical behaviour regardless of using thermo-mechanical beam elements or shell elements. A demonstration case of a timber-concrete composite slab is provided with thermal and thermo-mechanical responses, which imposes the adiabatic temperatures obtained from an FDS model of a compartment with a timber wall and a timber beam underneath a concrete slab. It demonstrates the purpose of the presented *OpenSees* development targeted.

Chapter 4: A Conceptual Design of Timber-insulation Mixed Slab Surface to Mitigate Large Open-plan Compartment Fire Development

Summary

As fire-safe timber-integrated slabs are the focus of this thesis, Chapter 4 transitions the focus from member-level modelling to compartment-scale fire dynamics by trying to address the critical issue of rapid fire spread in large open-plan compartments featuring timber ceilings. Inspired by previous work on discontinuous fuel fire tests where the use of clear spacing can mitigate or even prevent the spread of flames, this chapter proposes a novel fire mitigation strategy through the design of a timber-insulation mixed slab surface. This concept introduces alternating strips of non-combustible insulation material within the ceiling to limit the initial exposed timber area and to reduce the effect of the ignited timber strip on neighbouring timber strips, thereby disrupting the conditions that facilitate fast horizontal flame spread. Using high-fidelity CFD simulations calibrated against the Malveira fire test, the study evaluates different ceiling configurations with full-timber, non-combustible, and mixed surfaces, under the same fire load density. The results demonstrate that the mixed ceiling design effectively mitigates fire development and limits ceiling flame propagation, providing more than 20 minutes of delay in the compartment compared to a full-timber ceiling. This chapter thus converts earlier component-level thermal and structural insights into a practical fire safety design solution for modern mass timber buildings, emphasizing that strategic material configuration at the ceiling can meaningfully reduce fire spread without compromising timber's architectural or environmental advantages.

This chapter is based on “C. Chen, F. Wiesner, T. Chu, A. Usmani, L. Jiang* (2024). A conceptual design of timber-insulation mixed slab surface to mitigate large open-plan compartment fire development. **Journal of Building Engineering**, doi: <https://doi.org/10.1016/j.jobe.2025.112297>.”

4.1 Introduction

As timber is a renewable material, it has been widely used in modern buildings pursuing low-carbon design and construction. Due to the pre-fabrication opportunities of modern engineered timber products (e.g., glued laminated timber (Glulam), cross-laminated timber (CLT)) [37], timber has been used as structural materials in beams, columns, and floor slabs. Architectural aesthetics prefer to omit fire rated encapsulation of these timber structural members; this often necessitates deviation from prescriptive building codes. For timber exposed to fire, physical and chemical reactions occur: drying, pyrolysis, and ultimately oxidation of the char arising from pyrolysis.

To investigate the behavior of structural timber components in real fires, it is necessary to establish appropriate models for different stages. Chen et al. [92] developed a layered heat transfer model for timber materials based on the open-source platform *OpenSees* [47], enabling predictions of the thermal response of timber sections in realistic fires based on empirical formulae developed from a series of fixed and varying heat flux exposures tests for timber sections. Additionally, Chen et al. [50] previously demonstrated the use of beam or shell elements in the *OpenSees* for fire platform [49] to establish thermomechanical models and conduct analysis on timber structural components. These two tools can be combined with Computational Fluid Dynamics (CFD) simulations of compartment fire effects for a comprehensive thermomechanical analysis. In recent years, researchers worldwide have conducted many fire tests, including micro-scale cone calorimeter tests for timber materials [31, 32], meso-scale component furnace tests for structural timber elements [33, 34], and full-scale conventional compartment fire tests [7, 35, 36], to evaluate the performance of timber exposed to fires and the fire behavior of timber compartments. Fire tests in conventional compartments ($20 \text{ m}^2 \sim 40 \text{ m}^2$) [7, 35, 108] have demonstrated that exposed timber serves as a substantial fuel source during a fire, thereby accelerating fire growth and increasing heat release rates (HRR). The presence of exposed timber enhances the availability of combustible material, which intensifies the combustion process and leads to a more rapid spread of flames. Additionally, in scenarios with limited ventilation, the limited oxygen supply inhibits the efficient combustion of pyrolysis gases. This often results in incomplete combustion and promotes external burning within these compartments, further exacerbating fire dynamics and contributing to sustained high temperatures.

Modern architecture often features large open-plan interior spaces and oversized windows to meet aesthetic preferences and functional requirements. For example, a survey of the University of Edinburgh campus buildings revealed that [109] 16% of newly constructed buildings exceed the 500 m^2 area limitations imposed by traditional fire safety frameworks, which inevitably challenges conventional compartment fire safety frameworks [38]. Additionally, the fire safety design of conventional compartment fire frameworks is also inherently constrained by ventilation conditions, rendering the underlying assumptions less relevant for large and open-plan modern compartments [38-40]. Therefore, understanding

the fire dynamics in modern compartments is essential for developing effective fire safety design solutions. Rackaukaite et al. [42] conducted fire experiments inside a large and open-plan compartment within a 380 m² floor area, observing highly non-uniform spatial temperature and burning within the compartment. Regarding fire dynamics, the localized fire models utilized in the latest traveling fire methods are based on localized fire experiments with unconfined ceiling boundaries, neglecting the smoke effects generated by the fire. Khan et al. [106] conducted CFD simulations of localized fire experiments to evaluate the thermal impact on structural components and expanded the simulation models and analysis methods to localized fires in large compartments. Moreover, Nan et al. formulated a comprehensive structural model in OpenSees for fire [48] to explore the thermal impact on structural components under various traveling fire scenarios encompassing different parameters such as fire travelling directions and beam sizes. Additionally, considering that fuel distribution in realistic building environments is typically non-uniform, Nan et al. [46] investigated the impact of non-uniform fuel distribution on the evolution of fully ventilated compartment fires. Their findings suggested that assuming a uniform fuel load distribution might underestimate fire hazards, suggesting for the consideration of scenarios with non-uniform fuel load distribution in performance-based fire safety design. Furthermore, Hidalgo et al. [30] showed that, when combustible ceilings are introduced, the initial slow fire development of a traveling fire can rapidly transition to a full flashover fire. Therefore, understanding of the fire dynamics in large timber compartments is a critical knowledge gap that needs to be addressed. This is essential for establishing credible design fire scenarios and providing fire safety design methodologies for timber buildings to adequately mitigate associated risks. Based on emerging issues, a series of experiments on large open-plan compartments containing a 352 m² floor area was performed by Kotsovinos et al. and named the CodeRed series of experiments [29, 44]. This compartment was specifically constructed based on the x-ONE [42] and x-TWO [110] series test facilities with non-combustible concrete ceilings, which aimed to facilitate the comparison of fire dynamics observed in non-combustible compartments with those in compartments containing exposed timber. In the CodeRed experiments, the flame spread rapidly along the exposed timber ceiling inside the compartment and quickly reached the far end of the compartment compared to the non-combustible concrete ceiling in x-ONE [42] and x-TWO [110]; this different behaviour was due to the release and subsequent ignition of pyrolysis gases from the heated timber ceiling from the initial localized and slowly traveling fire.

Considering the fire development mechanism and fire simulation results in large open compartments with timber ceilings, this study aims to explore a conceptual novel design that utilizes a mixed surface of timber and insulation strips to mitigate the rapid spread of fire. To this end, various full-scale fire simulation models were established and run, including compartments with full-protection ceilings, timber-insulation mixed ceilings, and full-timber ceilings, respectively. Additionally, a preliminary investigation of various

timber strip widths was conducted to better understand how this design choice affects fire spread in large open compartments with partially exposed timber ceilings.

4.2 Effects of ceiling configurations to modern large open-plan compartment fire

4.2.1 Travelling fire behaviour in large open-plan compartment with non-combustible ceiling

Compared to conventional small compartments, open-plan designs lead to travelling fire dynamics and non-uniform thermal impact on structural components [39, 40]. The full-scale Malveira fire experiments conducted in Portugal [30] on large open-plan compartments have demonstrated three distinct fire modes along the floor plan and the transition between them, including slow travelling fires, rapidly growing fires, and fully developed fires with ventilation changes, as illustrated in Fig. 4.1. Notably, once the combustible ceiling (the cork layer in the Malveira fire test) ignites, it significantly alters the fire dynamics within the compartment. The ignition of the ceiling layer leads to a substantial increase in the overall heat release rate (HRR) due to the additional fuel provided by the timber material. This elevated HRR raises the ambient temperature rapidly, enhancing the release of pyrolysis gases from both the cork ceiling and floor wood cribs. In scenarios with limited ventilation, the accumulation of these flammable gases exacerbates the combustion process by providing a richer fuel-air mixture. Consequently, the intensified thermal environment and increased fuel availability accelerate the spread of flames throughout the compartment, leading to a swift transition to flashover. This rapid transition is characterized by the simultaneous ignition of all combustible surfaces, resulting in a fully developed fire. Such behaviour has been observed in experiments conducted at various scales [29, 45, 111, 112], highlighting the critical role of ceiling materials and ventilation conditions in influencing flashover.



Fig. 4.1. Diagram of travelling fire behaviour in Malveira fire test [30]: (a) Slow travelling fires; (b) Rapidly growing fires; (3) Fully developed fires.

4.2.2 Faster fire spread in large open-plan compartment with combustible timber ceiling

As mentioned before, structural timber has been widely used as structural elements in modern compartments, based on assumption of a sacrificial a char layer to maintain the load bearing capacity of underlying timber during a fire. However, the fire safety of buildings using full-timber components remains a concern. The CodeRed #01 fire experiment [29], which featured a fully exposed CLT ceiling, had a fire engulf the 34 m long 10 m wide compartment within merely 2 - 3 min after the CLT ceiling ignited. In

addition to this fully exposed CLT ceiling, the CodeRed #04 fire experiment [44] tested a compartment with a ceiling with 50 % of area encapsulated to observe fire spread on partially protected timber ceilings. In this test, the central 50 % area of the ceiling was protected. As shown in Fig. 4.2, the initial fire growth in CodeRed #04 is noticeably slower compared to CodeRed #01. According to the test report [113], this is primarily due to the higher moisture content in the wood crib and the partial failure of initial ignition in some methanol pans. Furthermore, since the encapsulation was located directly above the wood cribs, it was observed that during the early growth and stable spread stages, the flames did not directly affect the CLT ceiling. It was not until 23 min 53 s that the CLT ceiling was ignited, after which the flames quickly spread throughout the compartment, similar to what was observed in the CodeRed #01 fire test [29]. The fire duration, peak temperature, and heat flux were similar to those observed in the CodeRed #01 experiment [29]. Therefore, using a continuous block of encapsulation over a fraction of the overall ceiling area seems ineffective in mitigating the rapid-fire spread caused by timber ceiling burning.

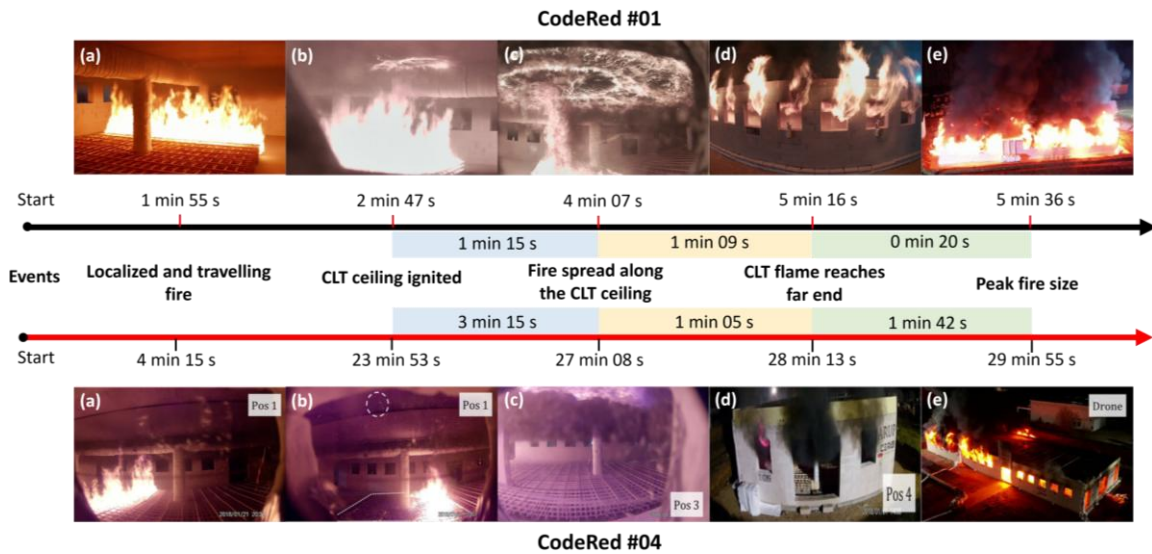


Fig. 4.2. Diagram of faster fire spread in large open-plan compartment experiments with exposed timber ceiling components: (a) CodeRed# 01 [29]; (b) CodeRed# 04 [113].

4.2.3 Mechanism of the faster fire development in compartment with continuous timber ceiling

Based on the observed compartment fire dynamics under different ceiling configurations mentioned above, it is essential to first understand the thermal response of timber ceilings under local fire impingement. As shown in Fig. 4.3a, timber ceiling exposed to compartmental fires are subjected to fire impact from the floor fuel load which initiates heat transfer with the timber surface, leading to heat propagation through thermal conduction, resulting in dehydration, pyrolysis, and charring of the original timber. Specifically, the pyrolysis of timber is typically divided into distinct temperature ranges based on thresholds at 200 °C and 300 °C: the sub-200 °C range encompasses dehydration drying and gradual pyrolysis, exhibiting stable pyrolysis within this interval, while rapid pyrolysis culminating in char occurs above 300 °C [24, 59].

Meanwhile, during the pyrolysis process, combustible gases will migrate along the cracks in the char layer to its surface. Continuous thermal exposure initiates the formation of a char layer on the timber surface, which progressively thickens as pyrolysis penetrates deeper into the timber interior. Additionally, prolonged exposure sustains the pyrolysis process, leading a reduction in the structural integrity of the timber, increasing the risk of structural failure or even contributing to the full development of a fire.

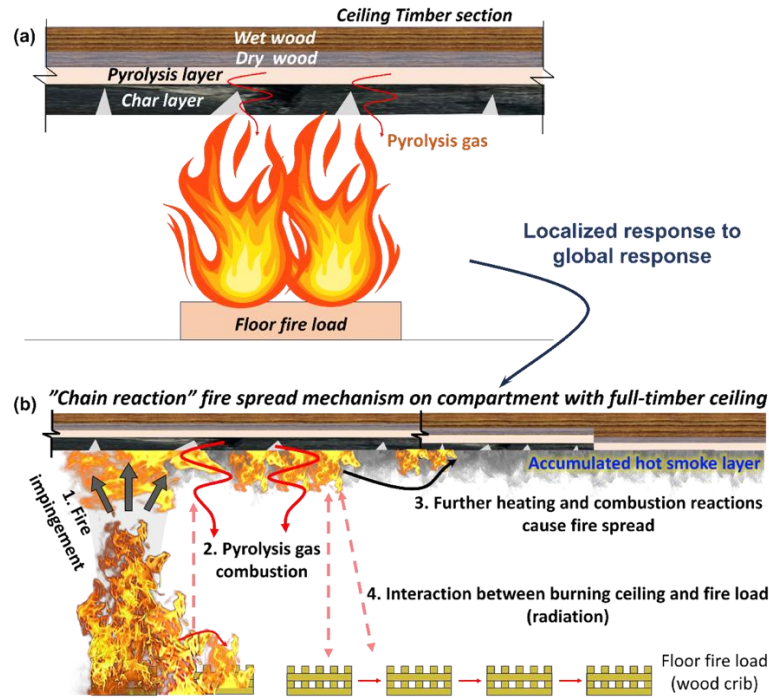


Fig. 4.3. Schematic illustrations from localize timber section to global timber ceiling exposed to fires: (a) The thermal response of ceiling timber section exposed to fire; (b) The mechanism of “chain reaction” for the faster fire development in compartment with the full-timber ceiling.

Based on the thermal response of timber ceilings exposed to localized fires and the fire dynamics within compartments with continuous timber ceilings, the concept of a "chain reaction" may be used to describe rapid fire spread. As illustrated in Fig. 4.3b, under the impact of localized fire, the timber ceiling undergoes pyrolysis, releasing combustible gases. Simultaneously, high-temperature smoke generated by localized fire gradually accumulates on the surface of the ceiling, preheating the timber ceiling in advance of the fire source. Subsequently, when the localized fire ignites the timber ceiling, a larger area of ceiling flame spread can be observed compared to compartments with non-combustible ceilings. This, along with the preheating effect of the high-temperature smoke layer, leads to the spread of flames along the ceiling from the region above the localized fire. This larger fire on the ceiling inevitably results in higher radiation to the floor fuel bed, subsequently spreading the flames from the originally localized fire to adjacent wood cribs. This growth induces heating and ignition further ceiling timber and floor fuel, and a fire could be encompassing the whole compartment within a very short period due to this “chain reaction” fire spread.

Mitigating such rapid-fire spread should aim to interrupt "chain reaction". In the following sections, a concept design that incorporates a combination of timber strips and insulation strips as mixed surface was introduced to interrupt sequential process of "chain reaction", thereby preventing the rapid fire

4.2.4 A hypothesis of timber-insulation mixed ceiling design

Based on the above, in large compartments with timber ceilings, the faster fire spread initiated from a localized fire may primarily be attributed to the "chain reaction" fire development mechanism. To mitigate such fast fire spread, this chapter proposes a conceptual design for timber ceilings comprising a mixed surface of timber and non-combustible insulation strips, as illustrated in Fig. 4.4a. The purpose is to reduce the initial exposed ceiling impinged upon by the initial localized fire source and the preheating effect to adjacent timber strips through insulation strips. Specifically, Fig. 4.4a depicts our preliminary design of fire-safe floor slabs based on mixed timber composite sections. This design involves grooving the timber slabs to embed insulation strips of specified width and thickness, complemented by a reinforced concrete upper layer to serve as the ultimate fire barrier. The details of mixed ceiling design still require more experimental validations. The objective is to reduce the initial exposure of the ceiling to the localized fire source and minimize the preheating effect on adjacent timber strips through the insulation strips. Here, it is important to note that the timber or mixed ceiling discussed in this chapter refers to the lower section of floor slabs, whereas the upper sections may have concrete layer and floor cover layers.

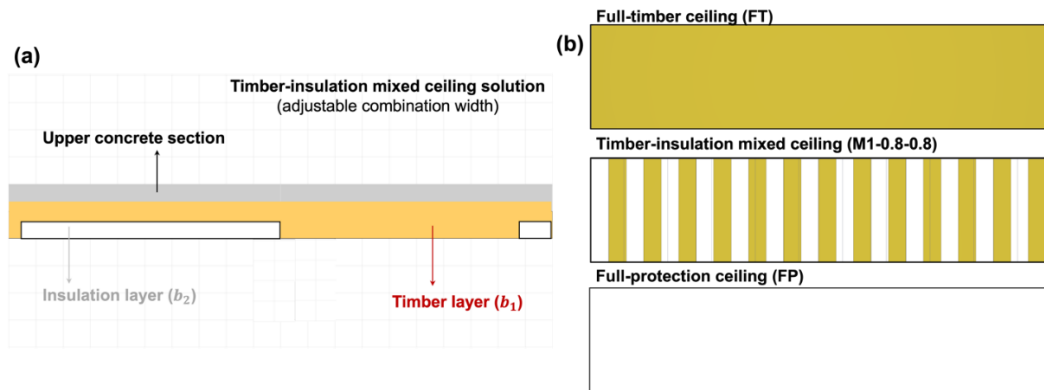


Fig. 4.4. Schematic: (a) Vertical section of the proposed mixed strip surface floor systems; (b) Initial version of the horizontal floor systems in different configurations.

Furthermore, the flexibility of this design can be adjusted by varying the widths of the timber strips (b_1) and the insulation strips (b_2); in the initial mixed ceiling configuration, both strip widths were set to 0.8 m. To explore this design option and identify a potentially optimal configuration, this chapter develops full-scale compartment fire numerical models to investigate the fire dynamics under different ceiling configurations. The considered cases are visualized in Fig. 4.4b which include full-timber ceilings (FT), initial timber-insulation mixed ceilings with 0.8 m strip widths (M1-0.8-0.8), and full-protection ceilings (FP).

4.3.1 Description of CFD fire models

Fig. 4.5. Experimental setup of Malveira fire tests: (a) Floor plan of the compartment with dimensions; (b) Schematic of section A-A; (c) Front view with five window openings.

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heat release rate per unit area (HRRPUA) of the burner ramped up linearly to 4200 kW/m² over 30 seconds, held constant at 4200 kW/m² for 180 seconds, and then decreased linearly to 0 over the remaining 420 seconds.

Table 4.1. Properties of material used for the tested compartment [116].

Properties	Density (kg/m ³)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)	Emissivity
Lightweight concrete	1375	753	0.42	0.9
Reinforced concrete slab (autoclaved aerated)	450	1050	0.16	0.9
Ceramic fiber	128	1130	0.02	0.9

As shown in Fig. 4.6, modelling the burning process of real crib wood sticks with a cross-section of 0.05 m by 0.05 m in the simulation would require a fine mesh, resulting in significant computational costs. Based on Janardhan et al.'s [118] equivalent wood crib method and in conjunction with its subsequent expansion by Chu et al. [119], the fuel bed in the Malveira fire test [30] was equivalently modelled, comprising two layers of pine sticks. Each stick was 1.2 m long with a 0.1 m by 0.1 m cross-section, spacing at 0.1 m in each layer, as shown in Fig. 4.6. To balance computational efficiency and accuracy in the present study, a uniform mesh size of 0.1 m was employed along the length, width, and height directions of the compartment in the CFD model. The overall fuel bed was 16.8 m in length and 2.4 m in width. In addition, the input parameter AREA_MULTIPLIER (AM) was employed to correct for the reduction in the mass loss rate (MLR) of stick burning due to decreased exposed surface area in the equivalent cribs and the definition of the input parameter BULK_DENSITY (BD) [118] was also incorporated to ensure the designed fuel density was adopted. The above critical parameters, AREA_MULTIPLIER and BULK_DENSITY, were set as 3.21 and 310 kg/m³, respectively.

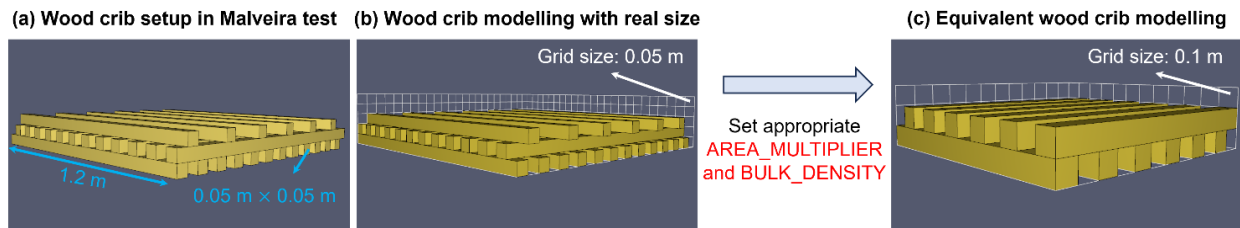


Fig. 4.6. Setup of the wood crib: (a) In Malveira fire test; (b) In FDS model; (c) In equivalent FDS model.

The combustion modelling of wood sticks was then addressed using a single-step pyrolysis model [118], which encompasses two parallel reactions: the pyrolysis of dry wood, resulting in the production of fuel vapor and char, and the evaporation of moisture content, producing water vapor. This approach is integrated into the CFD fire model by categorizing the fuel surface into a dry wood layer and a moisture layer based on the moisture content. The relevant thermal and chemical parameters are detailed in Table

4.2. For the cork layer in Zone B, the CFD model employed the ignition temperature model proposed by Chu et al. to simulate its ignition and combustion. The corresponding ignition temperature and HRRPUA were set at 400 °C [120] and 160 kW/m² [121], respectively. Due to the complexity of combustion of biopolymers, the above parameters may not necessarily represent all possible types of cork layer combustion.

Table 4.2. Thermal and chemical parameters used in the pyrolysis model [50, 116, 118].

Properties	Unit	Pinus Pinaster	Char	Moisture
Density ρ	kg/m ³	510	135	1000
Specific heat c_p	kJ/kg · K	20°C – 0.85 800°C – 2.73	1.08	4.18
Thermal conductivity λ	W/m · K	20°C – 0.07 800°C – 0.37	0.13	0.1
Emissivity e	—	0.95	0.98	—
Pre-exponential factor A_a	s ⁻¹	1.41×10 ⁵	—	9.57×10 ²²
Activation energy E_a	kJ/mol	8.97×10 ⁴	—	1.36×10 ³
Order of reaction n	—	1.69	—	3.31
Heat of reaction ΔH_r	kJ/kg	250	—	2500

4.3.2 Validation of CFD fire models

As shown in Fig. 4.5b, the Malveira compartment was divided through the placement of non-combustible concrete beams, effectively creating two distinct zones: Zone A, characterized by its non-combustible ceiling, and Zone B, featuring a ceiling composed of combustible cork layer. Numerical simulations were performed using the CFD model established according to the experimental parameters of the Malveira test [30]. The model accurately simulated both the travelling fire behaviours at 6000 s and the localized flashover at 13,300 s due to the combustion of the cork layer, as shown in Fig. 4.7.

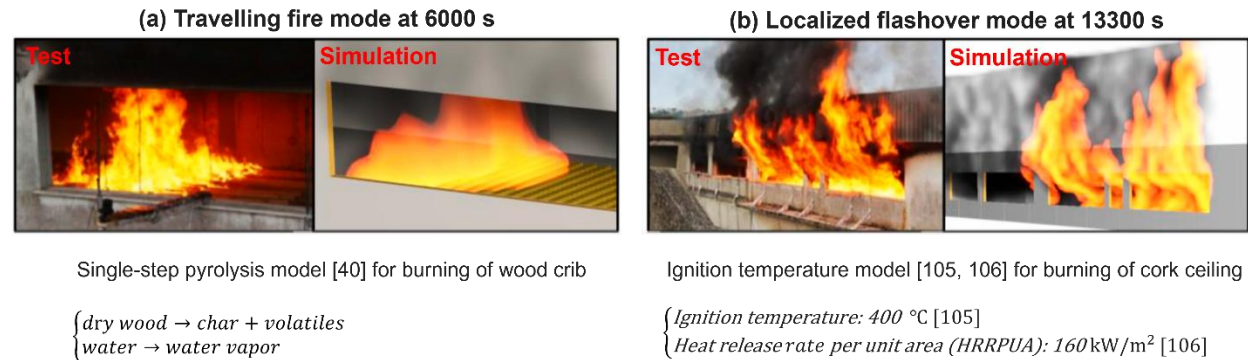


Fig. 4.7. Comparison between Malveira test results [30] and modelling results under assuming models.

In addition to the compartment fire development comparisons, two crucial parameters commonly used to characterize compartment fire development [122], namely the fuel mass loss rate and the total heat release

rate, were commonly used to characterize compartment fire. In the Malveira fire test [30], a false floor system was implemented, consisting of mass loss scales, and a protective layer composed of ROCKWOOL CONLIT™, 10 mm plasterboard board, and 20 mm particleboard, to monitor the mass loss of the wood cribs representing the designed fuel load. Subsequently, the compartment fire's heat release rate was estimated using a calorimetric method based on the mass loss rate of the wood cribs, but the combustion of the cork layer was not considered in this process as reported. The predicted results for the mass loss rate of the wood cribs and the compartment's HRR from the established CFD fire model were then compared with the results from the Malveira fire tests for which the HRR was based on a range of 12.8-20.4 MJ/kg for the heat of combustion of two species of pine wood [30]; this accounts for the uncertainty in the material and efficiency of the combustion, and therefore results in a range of HRR outcomes, as shown in Fig. 4.8.

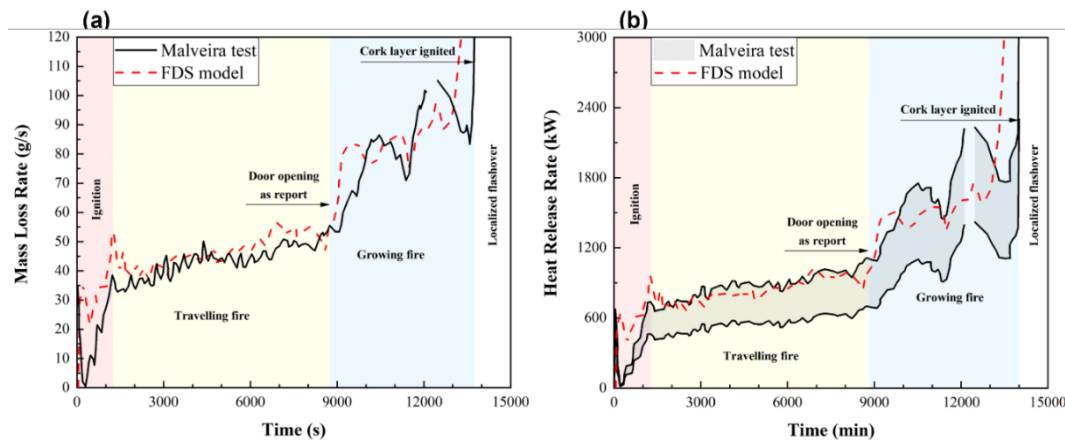


Fig. 4.8. Validation of the FDS model against the Malveira fire test [30]: (a) Evolution of the MLR of reaction fuel; (b) Evolution of heat release rates corresponding to the minimum and maximum HRR using 12.8 and 20.4 MJ/kg as the heat of combustion for timber material in test.

Overall, the time-varying MLR and HRR of the compartment fire provided by the fire model closely matches the experimental results. A slight overestimation was observed within the initial 1200 s, because it considered the heat release rate including the igniting fuel, which was not presented quantitatively in the report [30]. Subsequently, the overall mass loss rate of compartment fuel load and the heat release rate follow the measured values in the test. Despite some differences, this model offers acceptable performance of estimating open plan traveling fires for subsequent studies on the impact of different ceiling configurations within this large compartment.

4.4 Further exploration of fire dynamics in large open compartment using validated models

4.4.1 Impact of different fuel load layout on fire dynamics in compartment with timber ceiling

Based on the validated CFD fire model for the Malveira test [30], the beam and column arrangement in the compartments was removed and the ceilings were configured as continuous full-timber ceilings to

investigate the fire dynamics of large open compartments with full-timber ceilings. Notably, the combustion reactions of timber ceilings are simulated using the single-step pyrolysis model [118] mentioned above for wood cribs. Additionally, in realistic building compartments, the fuel load may be located in a discrete pattern. Based on this, under the same fuel load density, a large open compartment with a full-timber ceiling was selected as the baseline model. Two distinct layouts were employed: one featuring a continuous fuel arrangement similar to the Malveira fire test [30], and another involving a discrete arrangement of wood cribs on the floor to form a discontinuous fuel layout akin to the Kirby fire test [116], as illustrated in Fig. 4.9c and 4.9d.

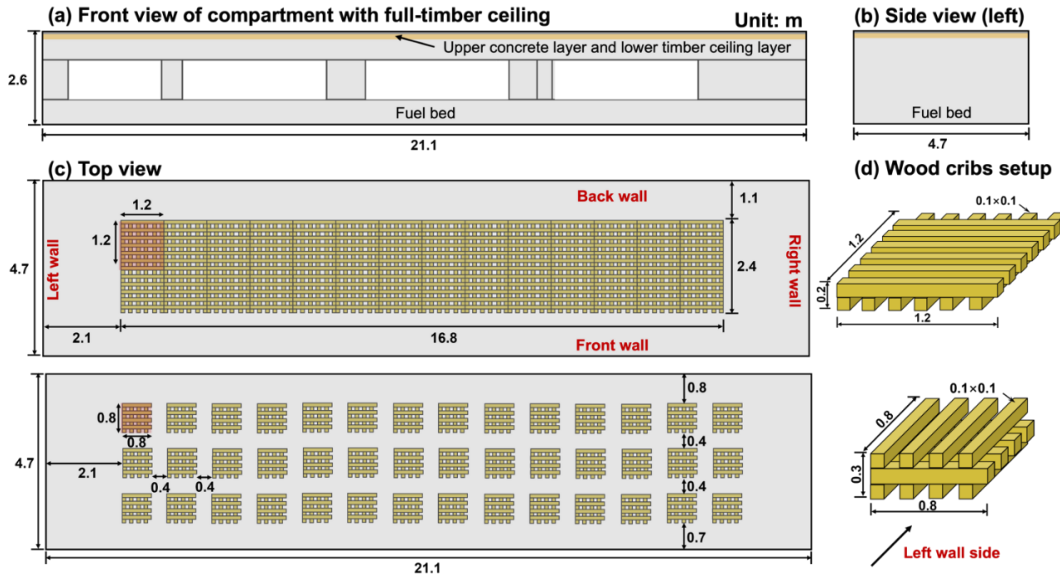


Fig. 4.9. Schematic diagram of simulated compartment with full-timber ceiling: (a) Front view; (b) Side view; (c) Top view of compartment with two different wood crib layouts; (d) Wood cribs setup.

In Fig. 4.10, black and red markers respectively highlight and label the timeline of same key events in the fire development within a large open compartment equipped with a full-timber ceiling, under both continuous and discrete wood crib arrangements. Specifically, for the continuous fuel bed case (a), once the preset burner is ignited, the wood cribs catch fire and the fire grows steadily. Within 7.5 min, a uniform flame front is formed across the width of the wood cribs. As flames continuously impinged on the timber ceiling, the ceiling was ignited at 8.0 min. Subsequently, the flames rapidly spread across the ceiling, spanning the entire length of the 21.1 m compartment after 10.0 min. In the subsequent period between 10.5 min and 19.0 min, flames propagated from the initially ignited wood cribs to the adjacent non-ignited areas. Notably, the fire front on the floor spread to the longitudinal compartment centre at 17.8 min, and to its back after 19.0 min, subsequently transitioning into fully developed external burning.

In contrast, for the discrete fuel bed case (b), a uniform flame front across the width of wood cribs forms at 9.2 min. Subsequently, the flames from the wood cribs impinge on the timber ceiling and ignite it

at 11.3 min, then causing a rapid ceiling fire that spans the entire compartment by 14.2 min. Due to interactions between the burning ceiling and the floor fuel load, the flames started to jump and spread to neighbouring cribs and then spread to the middle and back of the compartment by 21.0 min and 22.0 min, respectively, eventually transitioning to a fully developed external fire.

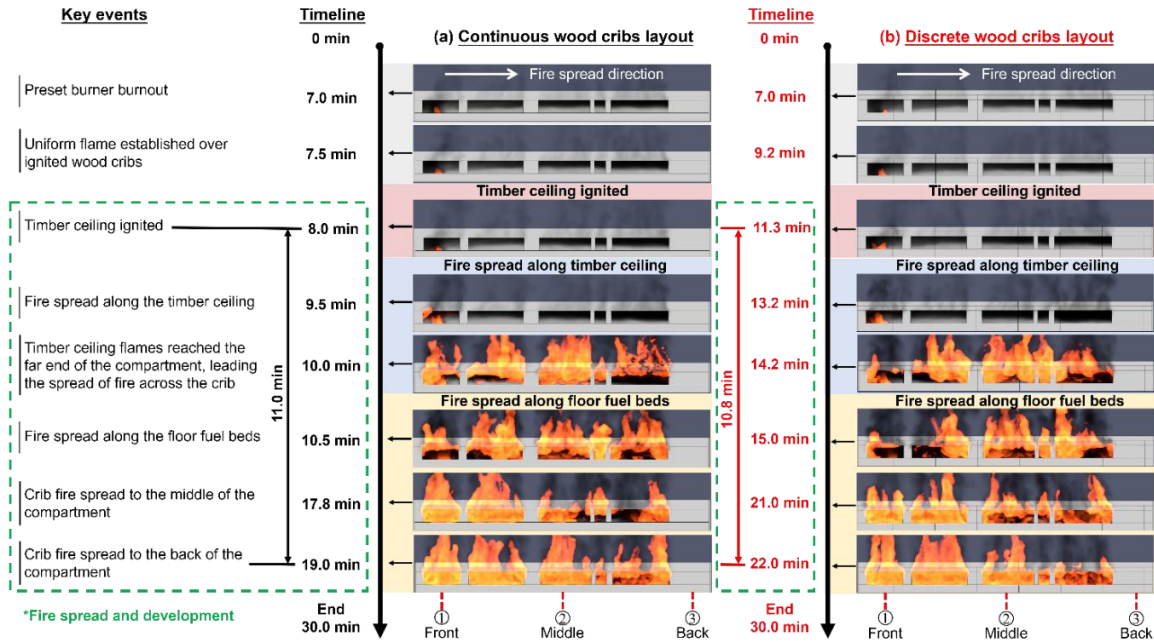


Fig. 4.10. Timeline of the simulation results of the compartment with full-timber ceiling under two different fuel layouts, presenting the key events and representative images.

Additionally, as shown in Fig. 4.9d, the discrete fuel bed configuration with the same fuel load density creates more layers compared to a continuous fuel bed. This initial configuration leads to higher flames that more readily impinge upon and ignite the timber ceiling, thereby accelerating flame spread. However, as shown in Fig. 4.10, it is worth noting that when comparing the time interval from the ignition of the timber ceiling to the fire spreading to the far end of the compartment, it was observed that this interval was 10.7 min in the compartment with the discrete fuel bed arrangement, only slightly faster than the 11.0 min observed in the continuous fuel bed arrangement. This suggests that it is feasible to mitigate the spread of fire by maintaining clear distances between combustible items in fire safety design.

4.4.2 Effect of timber-insulation mixed ceiling to compartment fire under discrete fuel layout

Given the crucial role of discrete fuel bed layouts in mitigating fire spread, this section examines and compares the fire dynamics in compartments arranged with discrete fuel beds under three different ceiling configurations (Fig. 4.9). Each composite slab features a lower ceiling layer, 0.15 m thick (timber, insulation, or a mixed layer), attached to an upper concrete layer measuring 0.05 m in thickness. For the simulation, all monitoring devices were positioned along the longitudinal axis. As shown in Fig. 4.11b, in the CFD fire

model, two heat flux gauges were placed to monitor surface heat flux on both the wood crib and the ceiling timber strip. One gauge was positioned 1.6 m from the ignition point, directly above the surface of the nearest wood crib. The other gauge was installed 2.3 m from the ignition point, just below the ceiling timber strip. These placements ensured accurate measurement of the heat flux changes affecting both the wood crib and the timber strip. Additionally, a thermocouple was placed 1.5 m from the ignition point below the ceiling to monitor the gas phase temperature.

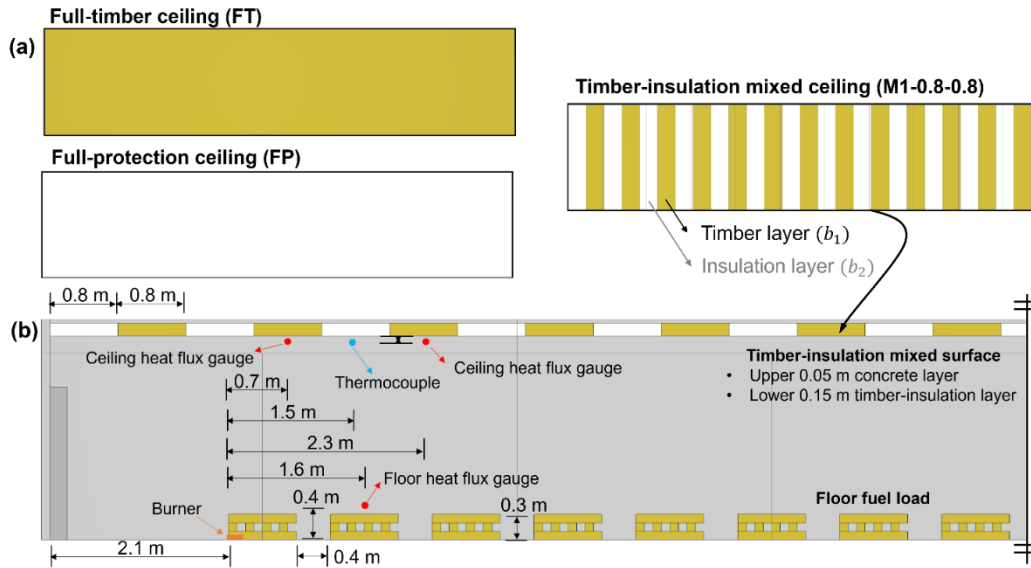


Fig. 4.11. Schematic configuration of the simulation cases: (a) Different ceiling configurations; (b) Compartment with timber-insulation mixed ceiling and layout of the measuring sensors.

The numerical simulation for each case was carried out separately, and the simulation results predicted different fire behaviour for the different compartment cases considered. As shown in Fig. 4.12a, focusing first on the initial development of the localized fire in the compartment with full-timber ceiling (FT) as it impinged the ceiling it could be observed that a uniform localized fire spanning the width of the wood cribs formed at 9.2 min. With the continuous impact of the localized fire, in the simulation with a full-timber ceiling, the timber ceiling was observed to ignite at 11.3 min, with a noticeable fire spread at 13.2 min, and timber ceiling flames to the far end of the compartment at 14.2 min. Under the heat radiation from the burning ceiling, the fuel load cribs located on the floor ignited at 15.0 min, with crib burning observed reaching the far end of the compartment by 22.0 min. For comparison purposes, the timeline of fire development in compartment with timber-insulation mixed ceiling (M1-0.8-0.8) and compartment with the full-protection ceiling (FP) at the same time points as the full-timber ceiling (FT) are shown in Fig. 4.12b. In comparison to full-timber ceiling compartment (FT), compartment with a timber-insulation mixed ceiling (M1-0.8-0.8) exhibited the stable localized burning after the initial contact of the fire with the ceiling, similar to the compartment with full-protection ceiling (FP).

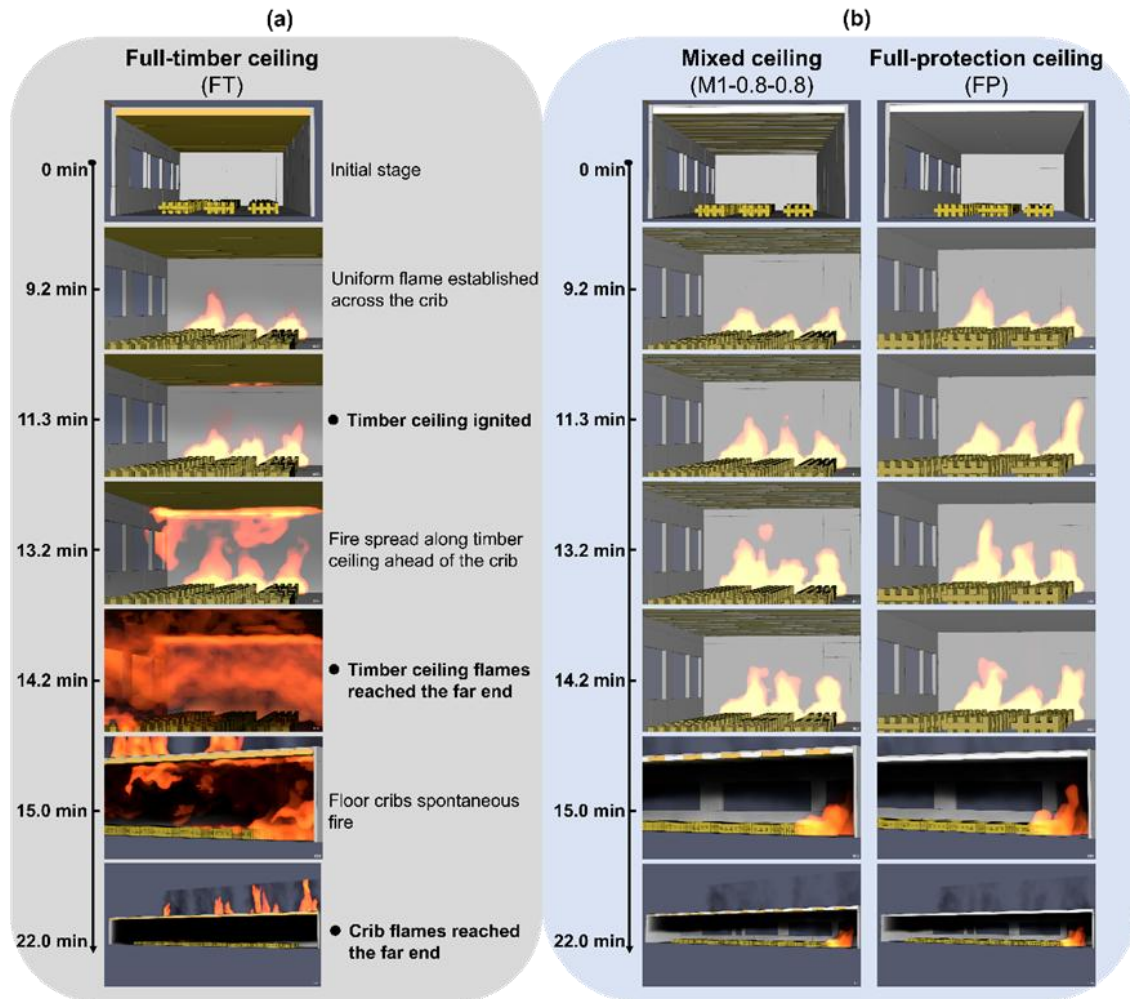


Fig. 4.12. Images capturing of simulated cases: the initial fire dynamics under localized fire impact for compartments equipped with different ceilings (interior and back views).

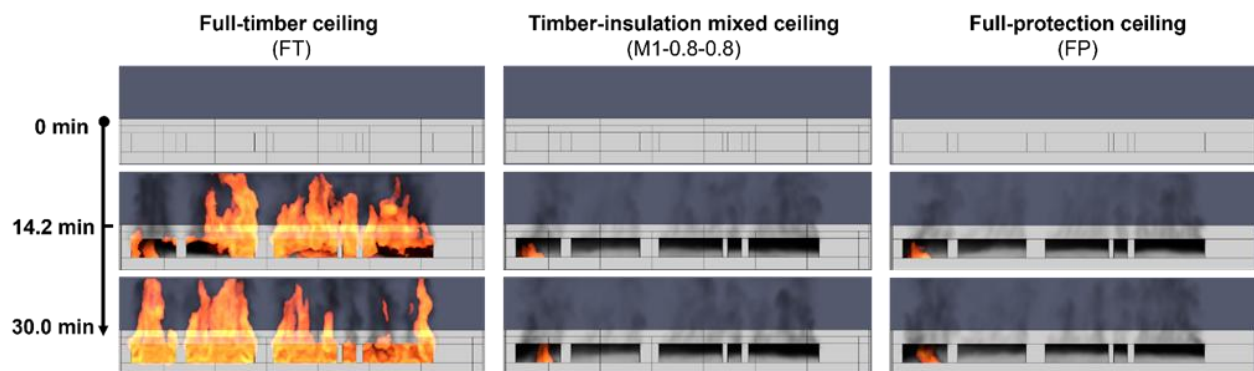


Fig. 4.13. Timeline of the numerical simulation cases for large compartment fire development with different ceiling configurations (front view).

Based on the detailed investigation and comparison of the initial development of compartment fires mentioned above, Fig. 4.13 provides a comprehensive comparison of the complete fire behaviour in simulated compartments with different ceiling configurations. In Case FT, a rapid spread of flames along the ceiling to the end of the compartment was observed at 14.2 min due to the initial contact of the localized fire with the ceiling, followed by the full development of compartment fire from 14.2 min to 30.0 min induced by the "chain reaction" fire development mechanism. In contrast, in Case M1-0.8-0.8, the fire developed more slowly. At 14.2 min, flames remained concentrated on the initially ignited wood cribs, and from 0 min to 30.0 min, a pattern of localized burning similar to Case FP was observed. This spotlights a key discovery that adopting a mixed ceiling strategy could potentially mitigate the rapid development of fires in open-plan compartments with exposed combustible ceilings.

4.4.3 Mechanism analysis of mixed strip strategy to mitigate rapid-fire development

Based on the observed efficacy of the strip model in mitigating fire spread in large open compartments, it is necessary to further confirm whether the mitigation mechanisms align with the expectations outlined in Section 2.4. To facilitate comparison with the mass loss rate of adjacent timber strips at the same position above the ignited wood cribs, the timber ceiling in the CFD model of the full-timber ceiling case was adjusted to consist of a series of uninterrupted continuous timber strips of 0.8 m each. Furthermore, to quantify the incident heat flux on the floor fuel bed caused by the spread of ceiling flames, heat flux gauges were placed at the surface of adjacent wood cribs located 1.6 m from the ignition point, as shown in Fig. 4.11b. This allowed a closer consideration of flame spread and its main drivers for the different ceiling configuration cases.

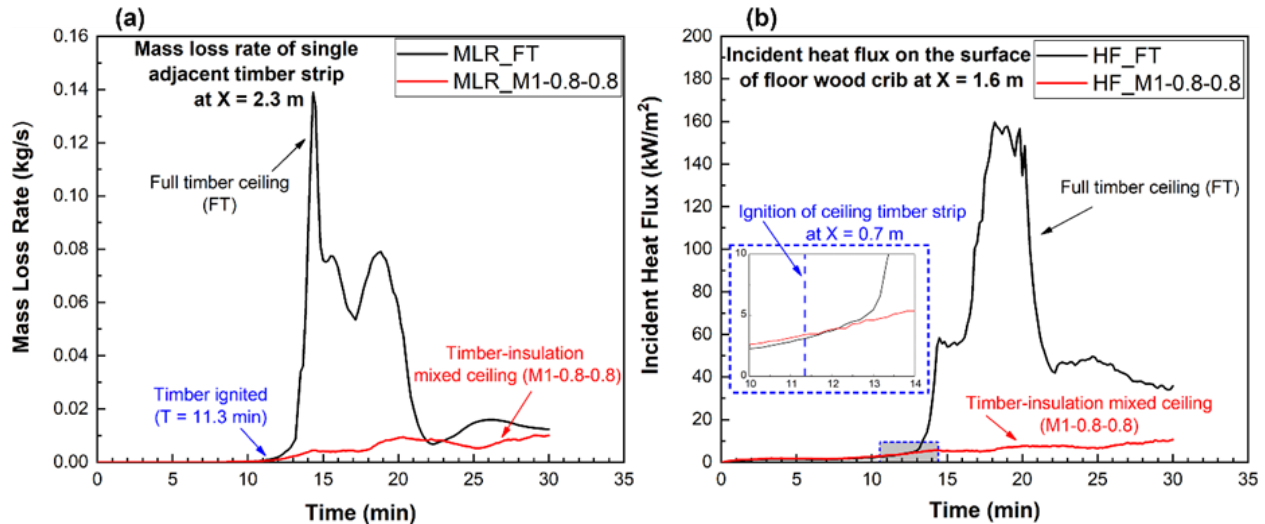


Fig. 4.14. Effects of mixed ceiling strategy on: (a) MLR of a single adjacent timber strip 2.3 m from ignition point; (b) Surface incident heat flux on the adjacent wood crib 1.6 m from ignition point.

As shown in Fig. 4.14a, in Case FT, the timber ceiling was ignited at 11.3 min, and with the intensification of pyrolysis combustion reactions, the rapid development of mass loss rate in adjacent timber strips was observed. However, in the mixed ceiling compartment (Case M1-0.8-0.8), the mass loss rate of timber strips at the same position increased more slowly and was markedly lower than the former. This indicates that the insulation strips in the mixed ceiling effectively reduce the preheating of adjacent timber strips from the flame jet due to the ignition of the timber ceiling. Additionally, in Case FT, after the timber ceiling was ignited at 11.3 min, the mass loss rate of the target timber strip located 2.3 m from the ignition point increased rapidly. Simultaneously, a marked rise in the incident heat flux was observed on the surface of the adjacent wood crib at a distance of 1.6 m from the ignition point, which indicates that the burning ceiling accelerates pyrolysis by radiatively applying the fuel load to the floor, as shown in Fig. 4.14b. According to the simulation results, the mixed ceiling strategy effectively disrupts the rapid fire spread mechanism by reducing the incident heat flux on adjacent timber strips and wood cribs. This lowered heat flux in turn slows the pyrolysis reactions of these timber materials, demonstrating how the proposed strategies can mitigate the overall fire growth in large timber compartments. The next logical step is to investigate the effect of width and spacing of the insulation strips on the ceiling, as described in the following section.

4.5 Effect of strip combination width on large open compartment fire dynamics

4.5.1 Fire dynamics of compartment with various strip width combinations

As mentioned in Section 3.1, the adjustability of strip widths in mixed ceiling allows for flexibility in design. It is important to note that in the investigation of different strip widths in the following subsections, it was ensured that all other input parameters (e.g., material properties, heat release rate per unit area of the wood cribs, and ventilation conditions) were consistent throughout the cases. As shown in Fig. 4.15a, while maintaining the area ratio of timber strips to insulation strips as around 1:1, three target configurations were tested: narrow strips (0.4 m, Case M2), medium strips (0.8 m, Case M1 – as investigated against the full ceiling), and wide strips (1.6 m, Case M3). The corresponding simulation results are plotted in Fig. 4.15b and 4.15c, showing different fire developments within the compartments.

In fire dynamics, a significant and rapid increase in the HRR of a compartment fire usually means that the compartment is evolving towards the fully developed stage, which leads to the spread of the fire to the surrounding area in a very short period, generating a larger fire size. In the compartment heat release rate (HRR) comparison depicted in Fig. 4.15b, it is apparent that, unlike the full timber ceiling (FT) configuration which undergoes rapid development starting at 11.3 min, all three strip width combinations exhibit a delayed onset of HRR acceleration. Among these, the 0.4 m strips (M2-0.4-0.4) and 1.6 m strips (M3-1.6-1.6) cases both show a similar delay of approximately 6.0 min. During this period, a low HRR

peak appeared at about 14.2 min, followed by a slight decline, before regaining acceleration around 19.2 min. In contrast, the 0.8 m strips (M1-0.8-0.8) case does not exhibit any obvious rapid-growth phase throughout the entire 30.0 min observation. Furthermore, as shown in Fig. 4.15c, the compartment fire dynamics at equivalent periods indicate that each phase of rapid growth is linked to pyrolysis combustion initiated by the adjacent combustible surfaces, thereby promoting rapid fire spread. While these strip configurations effectively delay the onset of rapid HRR growth, these do not permanently suppress the overall burning potential. Once beneficial conditions (e.g., sufficient heat feedback and available fuel) are re-established, the fire may continue to propagate, as shown by the progression observed between 19 min and 30 min in 0.4 m strips (M2-0.4-0.4) and 1.6 m strips (M3-1.6-1.6) cases.

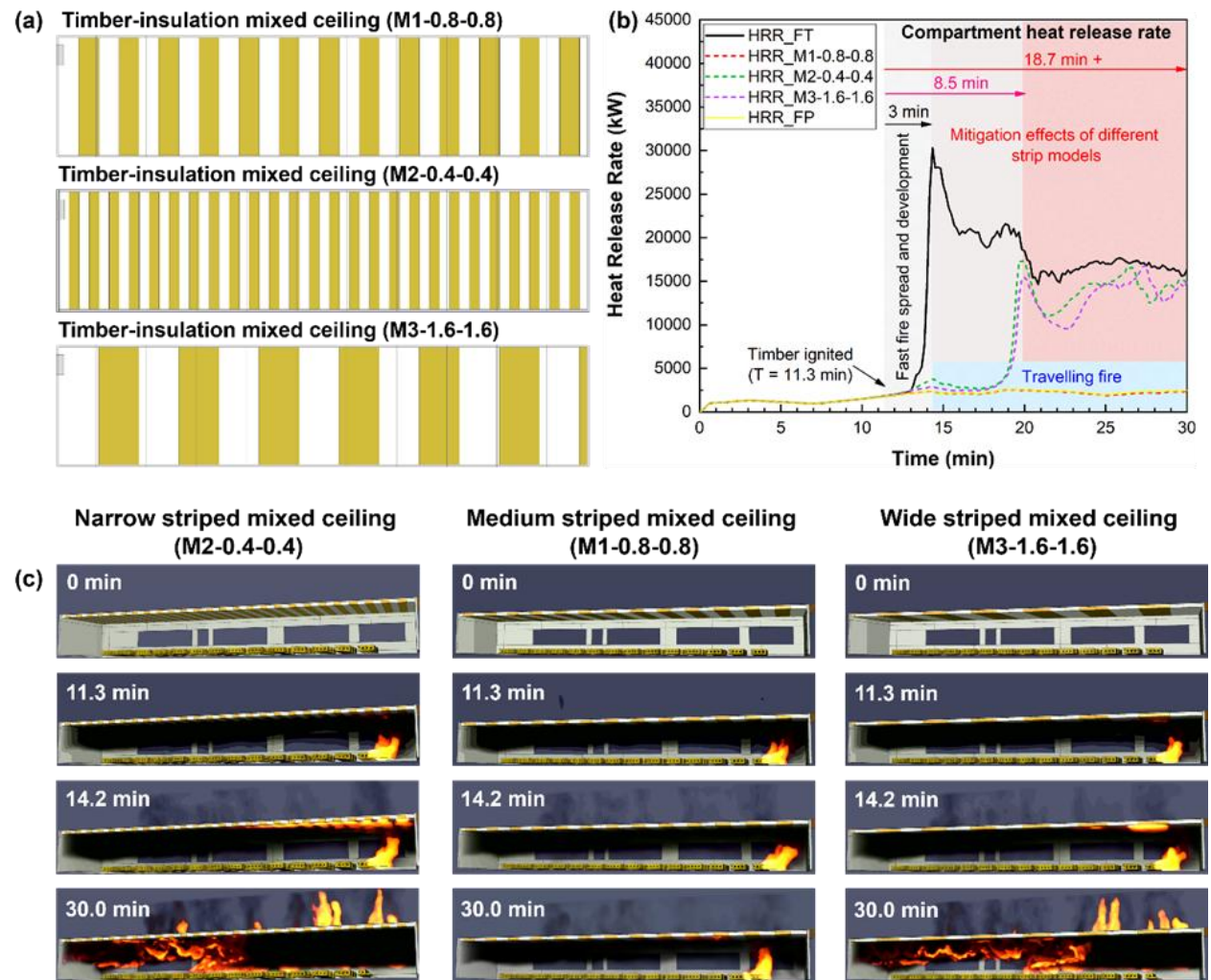


Fig. 4.15. Compartment fire simulation results with mixed ceilings: (a) The arrangement of mixed ceiling under three strip width combinations; (b) Compartment heat release rate evolutions; (c) Fire development inside compartments with various striped mixed ceilings (opening opposite view).

4.5.2 Discussion on ceiling flame jet length in compartments fire with various strip widths

Based on the differences in compartment fire dynamics mentioned above, this section further investigates the flame extension length and temperature profiles of ceiling flame jets following the interaction of initially localized wood crib flames with ceilings of different strip width combinations using the CFD fire model. The existing data on heat flux to the ceiling, gas temperature at the ceiling, and flame extension length patterns for the three configurations were studied. Additionally, as the burning ceiling affects the floor fuel load through radiation, the heat flux on the surface of the floor fuel bed was also used to evaluate the ceiling flame jet.

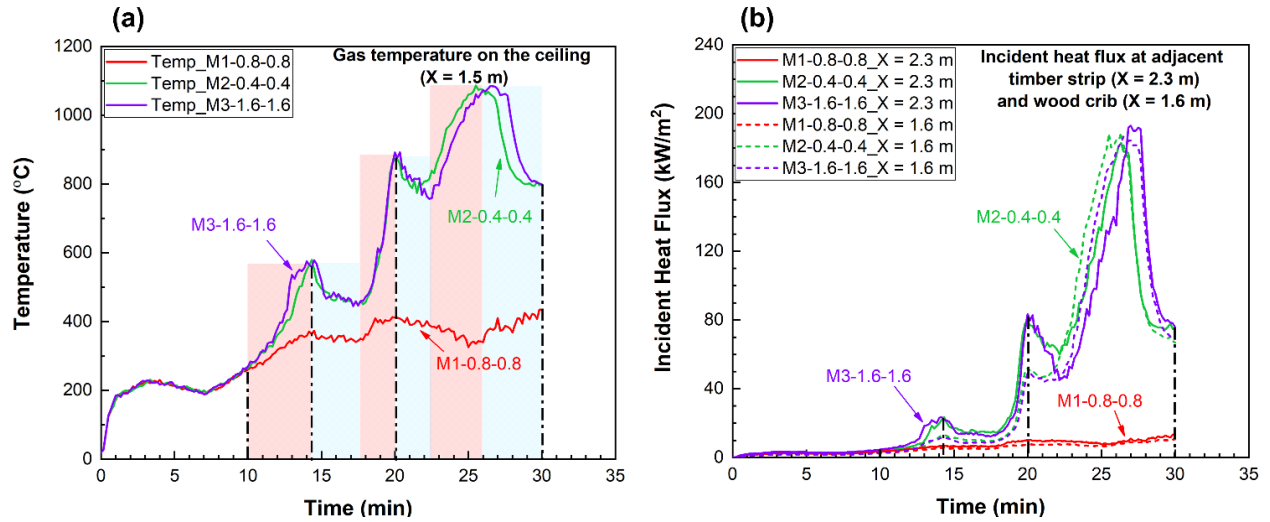


Fig. 4.16. Effects of strip width on: (a) Gas temperature on the ceiling; (b) Heat fluxes to adjacent ceiling timber strips and floor wood cribs.

Firstly, the gas temperature at the ceiling was measured as a function of exposure time. A sample plot of the gas temperature with time at a distance of 1.5 m from the ignition point on the ceiling is provided in Fig. 4.16a. Different gas temperature developments were observed around 10.0 min. Compared to the overall stable Case M1, the more densely spaced Case M2 and the more sparsely spaced Case M3 showed similar fluctuation trends: an initial increase, a brief stabilization, and then a decrease. The initial rise in gas temperature is likely due to the preset burner, and ignition and heat release from timber sticks of wood cribs and the subsequent decrease after brief stabilization could be attributed to the decline in HRRPUA of the burner in the fire model from 3.0 min to 7.0 min. In Cases M2 and M3, after 7.0 min, the burning intensity of the timber sticks in the wood crib increased, resulting in the earlier formation of a stable localized flame that impinged on the ceiling. By 11.3 min, the fire ignited the ceiling and intensified with further pyrolysis and combustion, rapidly forming a ceiling flame jet that extended beyond the insulation strips, further preheating and igniting adjacent timber strips. This led to a rapid temperature rise at the monitoring points. Additionally, the gas temperature is also influenced by window openings, changes in fire source intensity,

convection and airflow effects, mixing of external air with the smoke layer, and fluctuations in flame and thermal radiation.

Secondly, the heat flux development for the three ceiling configurations at 1.6 m on the adjacent wood cribs surface and 2.3 m on the timber strip surface from the ignition point is shown in Fig. 4.16b. The trends in heat flux were similar to the gas temperature development on the ceiling. In Case M1, the heat flux at both monitoring locations remained consistently below the minimum heat flux, 20 ~ 25 kW/m² [123, 124], for timber auto-flaming ignition under the short-term irradiation exposures (minutes), effectively mitigating the rapid pyrolysis and combustion of timber components within the compartment.

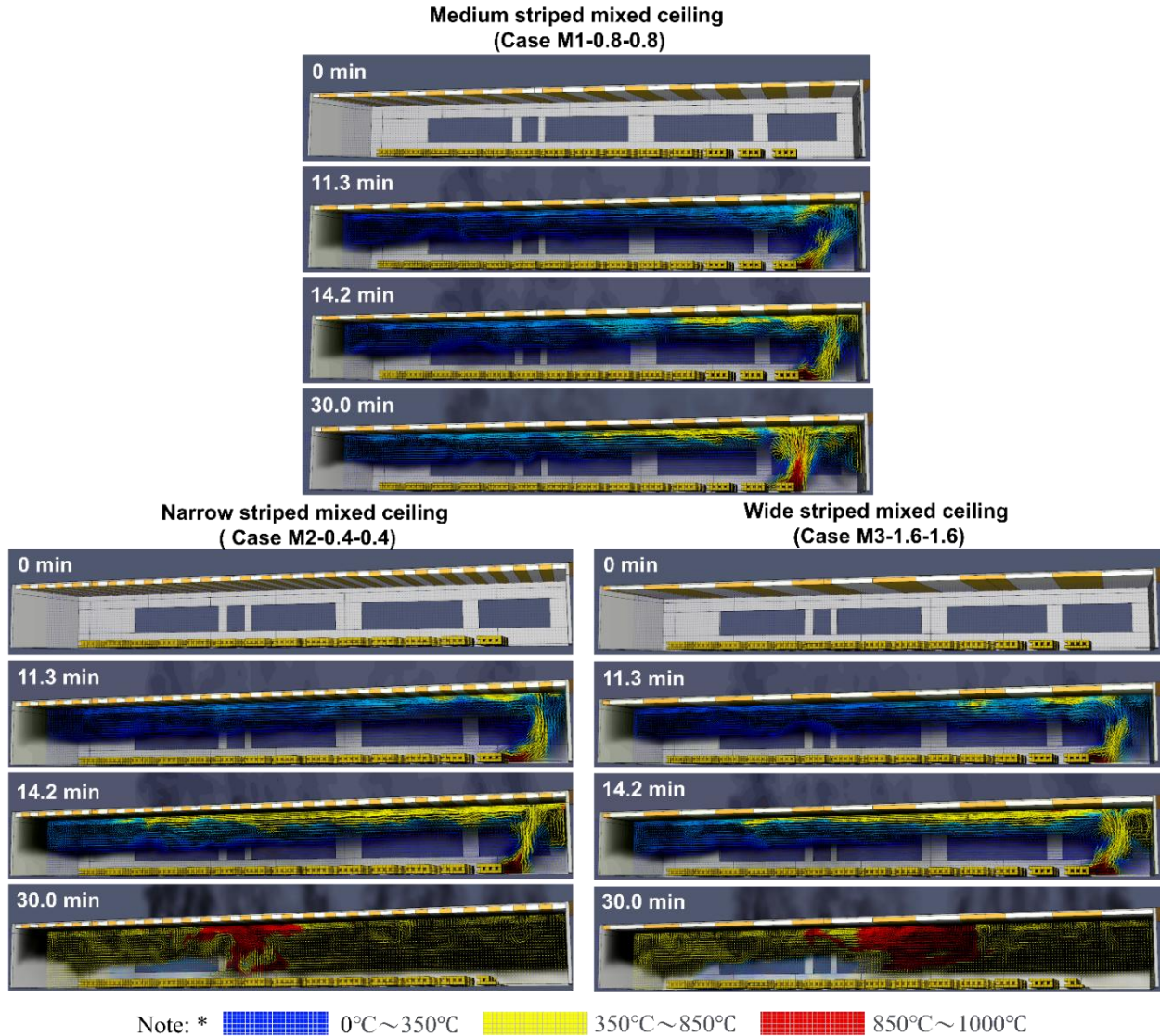


Fig. 4.17. Effects of strip width on flame extension length patterns (opening opposite view).

Finally, the comparison of the 2D slice vector temperature at different time points across the three compartments was conducted to observe the ceiling flame length patterns, as shown in Fig. 4.17. To simplify

visualization, the temperature slices were divided into low, medium, and high-temperature regions for comparison. Under the same fire load, Cases M2 and M3 exhibited more stable wood crib fire and higher temperatures at 11.3 min compared to Case M1, resulting in longer ceiling flame jets. This phenomenon may be attributed to the significant differences in local thermal conductivity and heat capacity caused by dense and sparse arrangements, leading to a faster temperature rise in the front of the compartment, as observed in the gas temperature development on the front ceiling in [Fig. 4.16a](#). At 11.3 min, the longer ceiling flame jet in Cases M2 and M3 caused more timber strips to undergo pyrolysis combustion. This, in turn, resulted in a further intensification of the ceiling flame jet in terms of length and area temperature during 11.3 min ~ 14.2 min. Ultimately, the difference in the burning ceiling area led to variations in the incident heat flux of the ceiling timber and ground fuel loads surface, as shown in [Fig. 4.16b](#). Subsequently, at 14.2 min and 30.0 min, the ceiling flame jet length in Cases M2 and M3 increased, indicating flame spread along the ceiling. This further led to increased surface heat flux on the floor fuel bed, accelerating the pyrolysis of the wood cribs and flame spread across the fuel bed. By contrast, Case M1, with the 0.8 m strip width combination, maintained localized burning and shorter ceiling flame jet lengths within 30.0 min, indicating more limited fire spread along the ceiling.

4.5.3 A summary of ceiling flames in compartment fires under various strip widths combinations

Based on the investigation into how variations in ceiling strip widths affect compartment fire behaviour, as shown in [Fig. 4.18](#), it was found that the characteristics of ceiling flames differed depending on the strip widths. Compared to the medium-width strip combination in Case M1, in Case M2, which featured denser strips, the narrow width of the insulation strips allowed the ceiling flames to leap across and ignite adjacent timber strips. Conversely, in Case M3, wider strip combinations led to more intense flame development after the ceiling wood was ignited, due to a larger available fuel area, compared to Case M2. The flames had enough intensity to ignite adjacent timber strips and also radiated sufficient heat to ignite nearby wood cribs, resulting in faster flame spread and fire growth. While the variations in flame behaviour observed with different strip width combinations suggest that strategic selection of strip dimensions can influence fire dynamics, part of this effect stems from the reduction of the total surface area of exposed wood, thus reducing the potential maximum heat release rate. This is in addition to the interruption of the ceiling flame spread 'chain reaction', which limits the amount of timber burning simultaneously, thus potentially providing a method to mitigate fire spread in large compartments. But the width of non-combustible strips must be carefully considered. In addition, before adopting the proposed strategy, it is important to note that the current study assumes that the predominant direction of fire spread is perpendicular to the strips, since here the large compartments are of high length-to-width ratio [30]. For different compartment geometries, fires may spread in multiple directions, which may reduce the effectiveness of fire mitigation, which requires further investigations.

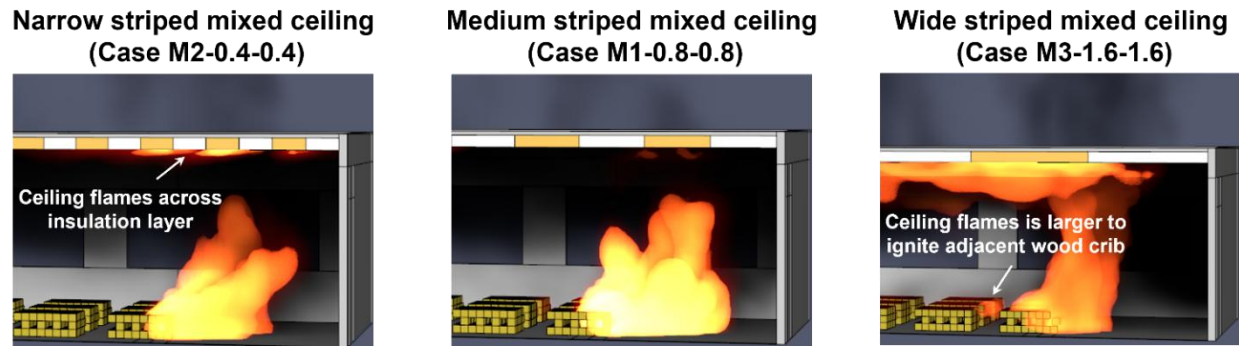


Fig. 4.18. Effects of ceiling flame inside compartments under different strip widths (Opposite view of the opening at the front of the compartment).

4.5.4 A brief overview of timber-insulation mixed slab application

While the current study focuses on introducing this concept and demonstrating its preliminary fire performance in large open compartments, and corresponding scaled tests can further validate and calibrate the proposed model, there are several ongoing and future works aimed at validating and refining this design. First, scaled slab tests with mixed ceiling are planned to investigate the connection details between insulation strips and the timber slab and the protective mechanisms of these strips when heat-induced deformation or cracking occurs in the timber section. This will facilitate the optimization of insulation strip embedding. Second, by extending the heat transfer (HT) module in *OpenSees* [47], thermal analyses can be carried out under various boundary conditions, ranging from prescribed fire exposures to those generated by CFD simulations, based on the open-source “OpenSees for fire” platform [48, 49]. The resulting thermal response will serve as a critical input for subsequent structural analyses. Meanwhile, the thermo-mechanical model for mixed timber two-way slabs (OPS-TM) is underdeveloped, which employs a unified reference-plane discretization with shell elements, incorporating ribbed cross-sections and real-time temperature loading to achieve integrated thermomechanical analyses of mixed sections. Finally, a thermomechanical analysis of timber-concrete composite slabs will be performed through the integration of CFD-based fire simulations and the *OpenSees* simulation platform, followed by extensive parametric studies. Finally, a full-scale test building will be constructed to conduct validation experiments under varying interior space dimensions, thereby evaluating the effectiveness of the proposed design concept.

4.6 Conclusions

This chapter implements a conceptual design using a timber-insulation mixed ceiling to mitigate fire spread in the large open-plan compartment. The relevant strategies have been implemented in a CFD fire simulation model and subjected to comparative analysis. A total of five cases were divided into two groups. The first group simulated the fire dynamics in compartments under the same fuel load arrangement but with different ceiling conditions: a timber-insulation mixed ceiling, a fully exposed timber ceiling, and a full-

protection ceiling. The simulation results further corroborated the conclusions of numerous existing experimental studies: in large open compartments with fully exposed timber ceilings, flames spread rapidly along the ceiling, and the burning ceiling exacerbates the spread of flames across the floor fuel through radiation, ultimately leading to the development of a catastrophic fire. However, in comparative simulations lasting up to 30 min, compartments with mixed ceilings effectively mitigated the rapid spread and progression of the fire, exhibiting localized burning similar to that observed in full-protection ceiling compartments.

The second group studied and discussed the impact of different strip width combinations on fire dynamics. This included strip combinations that are more densely spaced (M2-0.4-0.4) and less densely spaced (M3-1.6-1.6) compared to a baseline case (M1-0.8-0.8 strips). The results indicate that both more densely spaced and less densely spaced strip combinations, when coupled with the same ventilation condition, cannot completely limit the risk of rapid flame spread and fire development following the ignition of ceiling timber strips. Therefore, it is essential to conduct a performance-based investigation for various strip width combinations, in conjunction with effective ventilation, for improved evaluation of fire safety in timber compartments.

However, it is essential to acknowledge some limitations in the current studies, like the impact of window height parameter on the compartment smoke accumulation related to the incident heat flux to the ground fuel load which may contribute to more fire safety concerns. It should also be remembered that simulations are only as good as their underlying assumptions and input data. Variations in inputs can cause a variety of different model outcomes. The experimental validation of this mixed-ceiling slab concept is still outstanding and will be completed in our future work. Nevertheless, this conceptual design may provide an opportunity to design fire-safe timber slab solutions for future buildings, and the developed simulation allows to explore the interacting effects of various design options. The coupling of these models will also allow to consider if a slower compartment flame spread constitutes a desired design outcome – from a structural fire analysis a slower fire may be worse [20].

Acknowledgements

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Chapter 5: Applying Timber-insulation Mixed Ceiling Strategy in CFD Simulation of Large Open-plan Compartment with Non-uniform Fuel Load

Summary

Extending the ceiling design application established in Chapter 4, Chapter 5 investigates the fire behavior of large open-plan timber compartments under non-uniform fuel load conditions, which are more representative of real-world building environments. While previous studies usually assumed uniform fuel distribution, this chapter integrates the timber-insulation mixed ceiling strategy into scenarios with different fuel load distributions, beam configurations, and ventilation conditions. The fire dynamics in these scenarios are analyzed to understand how key design parameters, such as the width of timber vs. insulation strips and the spacing of fuel loads, influence flame spread and heat release. CFD simulations calibrated against the Malveira fire test reveal that non-uniform fuel distributions can intensify localized burning and increase the risk of ceiling flame extension and fast fire development, especially in the presence of continuous timber ceilings. In contrast, the alternating timber-insulation mixed ceiling design effectively mitigated flame spread. The results also demonstrate that appropriate fuel spacing, strategic beam arrangement, and sufficient ventilation further enhance this mitigation. Additional simulations exploring extreme fire scenarios confirm the robustness of this mitigation strategy even under adverse conditions, which can be implemented by dividing the fire zones via the arrangement within the compartments and adjusting the corresponding combinations of the mixed ceilings based on the flexible combination features. Chapter 5 concludes that the mixed ceiling strategy offers a dual benefit, which mitigates rapid fire spread in large timber compartments while also improving the structural stiffness of the slab by its configuration, thereby providing a reference solution of fire safety and structural performance-oriented future timber floor systems.

This chapter is based on “C. Chen, F. Wiesner, P. Kotsovinos, T. Chu, Y. Nie, A. Usmani, L. Jiang* (2025). Applying timber-insulation mixed ceiling strategy in CFD simulation of large open-plan compartment with non-uniform fuel load. **Fire Safety Journal** (Submitting revision).”

5.1. Introduction

In recent years, engineered timber products, such as glued laminated timber (glulam) and cross-laminated timber (CLT) [37], have gained popularity in modern architectural design due to advantages in prefabrication, carbon footprint reduction, and natural aesthetic appeal. Performance-based building regulations and multi-story timber projects have further promoted the global growth of timber construction. However, as timber use has expanded, new fire safety challenges have appeared. Timber's combustibility can lead to faster fire spread, larger flames, and longer burning durations.

Over the past few decades, extensive research has emerged on the thermal and fire behavior of timber, spanning from material-level studies to full-scale compartment experiments and advanced numerical simulations. At the material level, bench-scale experiment studies using cone calorimeters have been fundamental in characterizing the combustion properties of engineered wood products [25, 31, 63, 125]. Here are some selective examples: Tran and White [31] established correlations between wood density and burning rates under controlled radiant heat, while more recent work by Rinta-Paavola et al. [125] developed multi-stage pyrolysis models for spruce and pine that capture both smouldering and flaming behaviors. These studies provide critical input parameters for computational models of timber pyrolysis and ignition. At the structural component level, numerous experimental studies have investigated the thermo-mechanical behavior of timber elements under fire conditions [19, 33, 34, 81-83, 126, 127]. Furnace tests on beams, columns, and panels have been conducted to evaluate charring rates, load-bearing capacity, and failure modes. For example, Fragiaco et al. [34] examined the fire resistance of cross-laminated timber (CLT) panels under out-of-plane loading, and Gernay [19] later investigated the burnout resistance of timber columns, highlighting the importance of cooling phase effects. In compartment fire research, early studies often focused on smaller, ventilation-controlled enclosures with limited opening sizes [7, 35, 128, 129]. Comparative studies such as those by McGregor [35], Hadden et al. [7], McNamee et al. [128], Sun et al. [130], Liu et al. [131], Jiang et al. [132], and Wiesner et al. [133] demonstrated that exposed timber surfaces, whether as structural members or lining materials, can cause quicker fire growth and higher heat release compared to non-combustible enclosures, because timber produces pyrolysis gases when it burns. However, such compartments where a significant portion of the combustible gases burn as external flames [134] differ fundamentally from modern open-plan layouts in both geometry and ventilation conditions. To better understand fire dynamics in large, open spaces, several experimental campaigns have been conducted over the past decade. Notable examples include the Edinburgh travelling fire experiments [135], the x-ONE fire test [42], and the Malveira fire test [30]. The results demonstrated that such modern compartments were more prone to travelling fires [39, 40], characterized by non-uniform temperature fields [39, 136, 137]. Although recent travelling fire experiments [30, 41, 42, 135, 138, 139] have revealed fire behavior in large open-plan compartments, however, primarily featured non-combustible linings. More recently, the focus

has shifted to compartments with exposed timber surfaces. Nothard et al. [112] revealed the combined effects of ventilation, fuel arrangement and exposed CLT area on fire dynamics in a medium scale open spacing experiment, and Su et al. [140] evaluated fire spread, temperature distribution and timber char progression in a full-scale mass timber-frame fire test. In addition, Kotsovinos et al. [113, 141] conducted the CodeRed series of experiments in a 352 m² open-plan compartment. CodeRed-01 [141] was designed to compare fire dynamics in compartments with a full and unloaded CLT ceiling to those observed in non-combustible compartments, such as the x-ONE test facility [42]. It is worth noting that while most CLT slabs in real buildings are designed as load-bearing structural members, few fire tests have actually incorporated sustained loads, largely because the timber's contribution to fire dynamics has been the primary research focus. In the CodeRed-01 experiment [141], it was observed that the CLT ceiling was ignited by localized fire from the wood crib within 3 minutes after ignition and the fire engulfed the compartment within 5 minutes. Given the observed rapid-fire development driven by pyrolysis combustion of continuous CLT ceilings under localized fire impingement, as a subsequent experiment to the CodeRed-01 test, 50% of the unloaded CLT ceiling area above the floor wood crib was partially encapsulated in the subsequent CodeRed-04 experiment [113] to mitigate this fire risk. Although encapsulation delayed ignition, once the remaining unencapsulated CLT ceiling was ignited, the flames still spread rapidly again. The duration of the fire, peak temperatures, and heat flux were similar to those observed in CodeRed-01 [141], indicating the necessity for alternative or additional mitigation strategies. Similarly, the FRIC-01 test [45] in a 95 m² compartment with exposed and unloaded CLT ceiling demonstrated cyclic “wave and retreat” fire behavior under enhanced ventilation conditions, which is different from the rapid flashover observed in CodeRed-01 [22] after the ignition of the ceiling. The above-mentioned experiments underscore the interaction between ventilation and fire dynamics of large open timber compartment.

Parallel to experimental advances, computational modelling has greatly enhanced the understanding of timber compartment fires. For timber material level, such as the heat transfer analysis of timber section, current modelling practice provided in Eurocode 5 (EC5) [8] allows for predicting the thermal responses of timber sections in standard fire exposure. To adapt the EC5 model to non-standard fire scenarios, König and Walleij [25] proposed an experimental-based method to calibrate thermal property parameters for more accurate predictions under parametric fires. Zhang et al. [83] developed an energy-based time-equivalent approach (EBTEA) for defining equivalent standard fire loads, though it still neglected the heat generated by timber combustion. While the physics-based Gpyro model [65] incorporates complex chemical and physical mechanisms at the microscale and exhibits high simulation accuracy, its technical complexity hinders its widespread use in engineering design. Alternatively, Hopkin's model [66], inspired by the ‘heat of hydration’ concept, offers a simplified method to account for combustion heat, yet requires further refinement and validation under diverse non-standard fires. For the structural timber members, such as

thermo-mechanical analysis for modern engineered timber components, advanced computational models have been developed to predict the thermo-mechanical behavior of structural timber members exposed to fires by using finite element software, such as SAFIR [126], ABAQUS [34, 88], and OpenSees [50, 90]. In particular, Chen et al. [50] further developed the prediction of the thermo-mechanical response of structural timber components under non-standard fire actions by considering the effect of timber combustion on heat transfer within the timber cross-section, which extends beyond simplified code-based methods (e.g., EC 5 [8]). Additionally, Nan et al. [46] developed a comprehensive structural model in OpenSees to study the effects of travelling fires on structural components, taking into account variables such as fire direction and beam sizes. For the fire dynamics studies related the compartments with timber surface, such as CFD, equipped with advanced pyrolysis models, have been validated against large-scale tests and are capable of simulating flame spread and gas-phase combustion in timber-lined compartments [e.g., 29,38]. For instance, Hayajneh and Naser [142] demonstrated that a calibrated FDS model could accurately reproduce temperatures and burnout times in a multi-story CLT building fire. In response to the challenges posed by travelling fires in modern large open compartments, Khan et al. [106] used CFD simulations to evaluate the thermal impacts on structural components in localized fires and extended their models to larger compartments. To address the ineffectiveness of continuous block encapsulation methods in the CodeRed series tests [113, 141], Chen et al. [143] thus proposed a timber-insulation mixed surface design for composite slabs, verified through full-scale CFD simulations, which showed potential in mitigating the fire spread. The proposed system is also envisaged as load-bearing, in line with the structural role of most CLT slabs. However, in the present study we primarily focus on its impact on fire dynamics as the first step, before moving towards full structural performance assessment under combined fire and load.

Despite these advancements, existing studies assume uniform fuel layout and standardized ventilation conditions, which often do not reflect real scenarios. Recent work by Nan et al. [46] has shown that non-uniform fuel layouts can lead to more severe and rapid fire than uniform arrangements, highlighting the need to incorporate challenging fuel distributions in fire safety assessments. Furthermore, the interaction between initial compartment parameters, including structural beams and ventilation configurations, and the evolution of fire dynamics requires further investigation.

Against this background, the study herein employs a validated full-scale CFD model to investigate the fire dynamics of large open timber compartments with non-uniform fuel layouts, filling an important gap in current research. In addition, the effectiveness of an proposed timber-insulation mixed ceiling design [143], developed to mitigate rapid ceiling fire spread, is further tested under non-uniform fuel conditions and in combination with other fire safety measures. Here, it is important to note that the timber or mixed ceiling discussed in this chapter refers to the lower section of floor slabs, whereas the upper sections may

cycle. In Fig. 5.2c, once the CLT ceiling was ignited, the fire dynamics changed, with accelerated flame spread across both the ceiling and the wood cribs. After the CLT ceiling ignited, the fire did not transition directly to flashover as in CodeRed-01 [141]. Instead, it entered a cyclic “wave-and-retreat” regime: flames surged beneath the ceiling, then briefly receded, yet every surge intensified crib burning and raised the temperature in the compartment, even in areas remote from the ignition point.

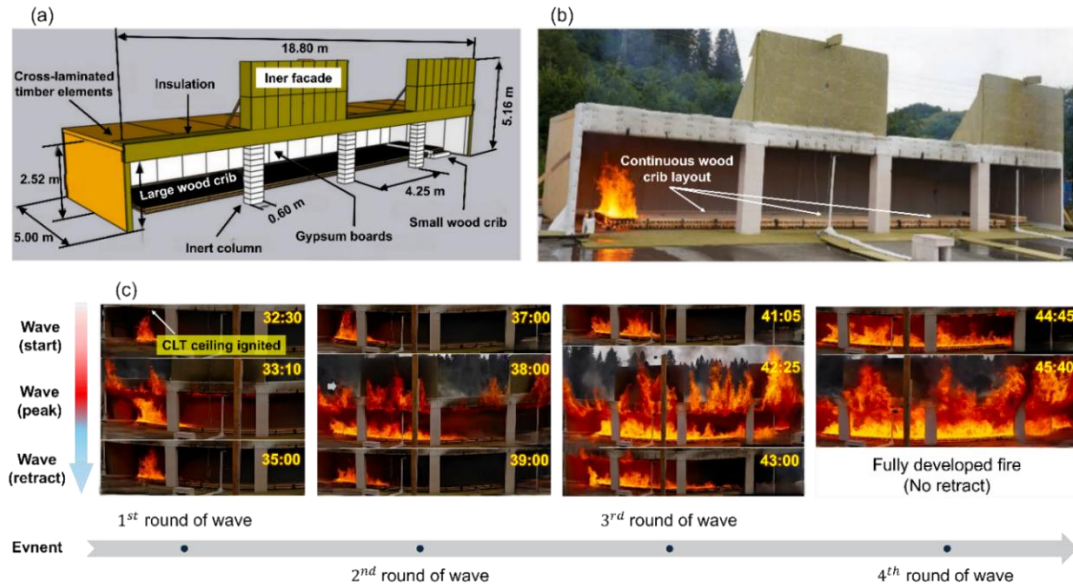


Fig. 5.2. Diagram of FRIC-01 test [45]: (a) Sketch of the compartment; (b) Continuous wood crib arrangement; (c) Fast fire development characterized by flashing waves after ceiling ignition.

5.2.3. Mechanism of fast fire spread in large open compartment with continuous timber ceiling and the proposed timber-insulation mixed ceiling strategy for fire mitigation

Based on the observations of fire dynamics in large compartments with continuous timber ceilings, it is evident that once the timber ceiling ignites, it results in rapid fire spread and development within the compartment. This phenomenon is due to the ongoing pyrolysis and combustion reaction of the timber ceiling under localized flame exposure [143, 145]. As illustrated in Fig. 5.3a, when a localized fire occurs in a compartment with a continuous timber ceiling, the ceiling begins to pyrolyze partially, releasing flammable gases. Hot smoke accumulates in the space above openings and the ceiling and preheated timber sections distant from the fire source. Subsequently, when the localized flames reach and ignite the timber ceiling directly above, the combined effects of localized combustion and preheating from the smoke layer cause the fire to quickly spread to unignited areas. This burning ceiling further accelerates pyrolysis, combustion, and flame propagation across the floor's fuel load through radiative heat transfer, ultimately resulting in a fully developed fire in the compartment.

Inspired by fire tests conducted by Nan et al. [46] for discontinuous fuel loads, which showed that sufficiently clear gaps between wood cribs in discontinuous fuel loads can effectively slow or even prevent

fire spread, a conceptual mixed timber composite (MTC) slab design has been proposed by Chen et al. [143, 146, 147] and demonstrated through full-size and high fidelity CFD fire modelling to be effective in mitigating fast fire spread in compartments by reducing the area of timber initially exposed to localized fires and by reducing the preheating effect on adjacent timber strips through the insulating gaps. Specifically, Fig. 5.3b depicts our preliminary design of fire-safe floor slabs based on mixed timber composite sections. This design involves grooving the timber slabs to embed insulation strips of specified width and thickness for partially encapsulating timber, complemented by a reinforced concrete upper layer to serve as the ultimate fire barrier. The insulation layer was represented by a non-combustible mineral wool product (ROCKWOOL CONLIT™). Its thermal properties were defined in the CFD model with a density of 80 kg/m³, specific heat of 0.84 kJ/kg·K, and thermal conductivity of 0.034 W/m·K, implemented as an INSULATION material. This allowed the model to capture the thermal effect of the encapsulation without involving additional combustion reactions. The details of mixed ceiling design still require more experimental validations and related studies [143] also highlighted retention of flexibility for different combinations through the widths of timber strip (b_1) and insulation strip (b_2).

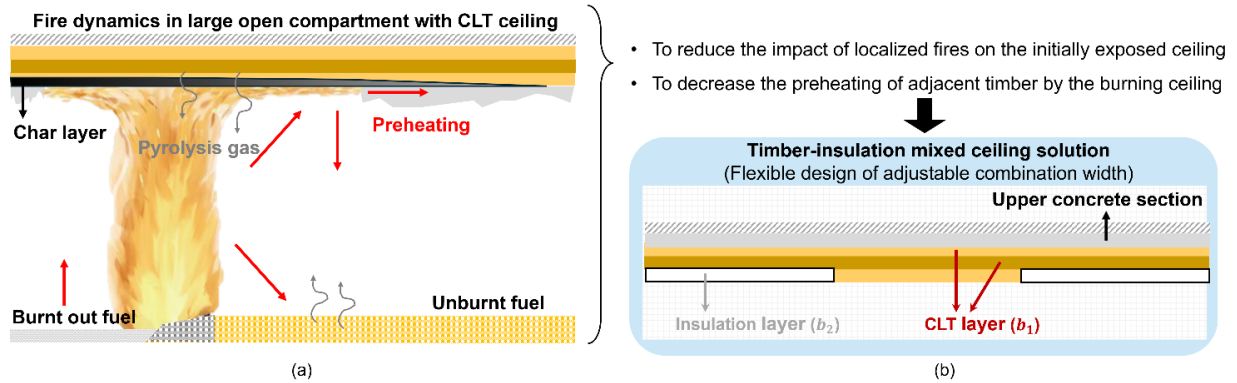


Fig. 5.3. Schematic diagrams: (a) The mechanism of the fast fire development of large open compartments with the continuous timber ceiling; (b) The proposed mixed timber composite (MTC) slab for fire mitigation in large open-plan compartments.

In addition, we would like to emphasize that in this work, the terms protection or protected (e.g., “full-protection ceiling”) are used later specifically to denote cases where an insulation material layer fully replaces the lower surface layer, thereby completely encapsulating the upper timber layer like a non-combustible concrete ceiling. In our proposed mixed design, the timber regions directly above the insulation strips are thus treated as encapsulated, while the remaining regions are exposed.

5.2.4. Validated CFD fire model as the baseline model

A CFD fire model was developed using FDS 6.8.0 [143]. The model was primarily calibrated and evaluated against experimental data from the Malveira fire test [30], which provided a baseline for simulating key phenomena such as travelling fire spread and localized flashover under open-plan conditions.

While this validation against a full-scale experiment enhances confidence in the model's capability to represent observed fire dynamics in large compartments, it is acknowledged that further validation across a wider range of scenarios would strengthen the model's generalizability.

In this model, to reduce the computational cost of simulating real wood sticks with a cross-sectional area of $0.05 \text{ m} \times 0.05 \text{ m}$ that would require a fine mesh, the equivalent wood crib method [119] was used to model the fuel load composed of $1.2 \text{ m} \times 0.1 \text{ m} \times 0.1 \text{ m}$ sticks used in the test, with *Pinus pinaster* cribs ($\rho = 510 \text{ kg/m}^3$, moisture content $19 \% \pm 6 \%$, effective heat of combustion 18 MJ/kg) represented via the AREA_MULTIPLIER and BULK_DENSITY parameters as per the established approach [118, 119]. Therefore, a uniform mesh size of 0.1 m was adopted along the length, width, and height directions of the compartment in the CFD model. The radiative fraction of the combustion reactions was set to the default value of 0.35, a common empirical setting for wood crib fires in FDS. Boundary conditions were defined to represent the experimental environment: all walls and the floor were modelled as adiabatic rigid surfaces to conservatively simulate heat accumulation, while window openings were treated as open vents with ambient conditions set to 20°C and atmospheric pressure, allowing natural exchange of smoke and air. The ignition was provided by a linear burner whose HRRPUA ramped $0 \rightarrow 4200 \text{ kW/m}^2$ in 30 s, held for 180 s, then decayed linearly to 0 over 420 s. It should be noted that the timber layers in both the wood stack and MTC use the same timber material. To characterize their combustion, a single-step pyrolysis model [118] was incorporated as comprising two parallel reactions: the pyrolysis of dry wood, resulting in the production of fuel vapor and char, and the evaporation of moisture content, producing water vapor, the established model characterized the combustion of the fuel. As illustrated in Fig. 5.4, the predicted heat release rate (HRR) and mass loss rate (MLR) showed good agreement with test data. Additionally, the model could also accurately reproduce the key fire phenomena observed in the test, including the travelling fire behavior at 6000s and localized flashover at 13300 s, as shown in Fig. 5.4b. Despite some discrepancies, the model demonstrated acceptable accuracy in estimating open-plan travelling fires and is therefore suitable as a baseline model for subsequent studies.

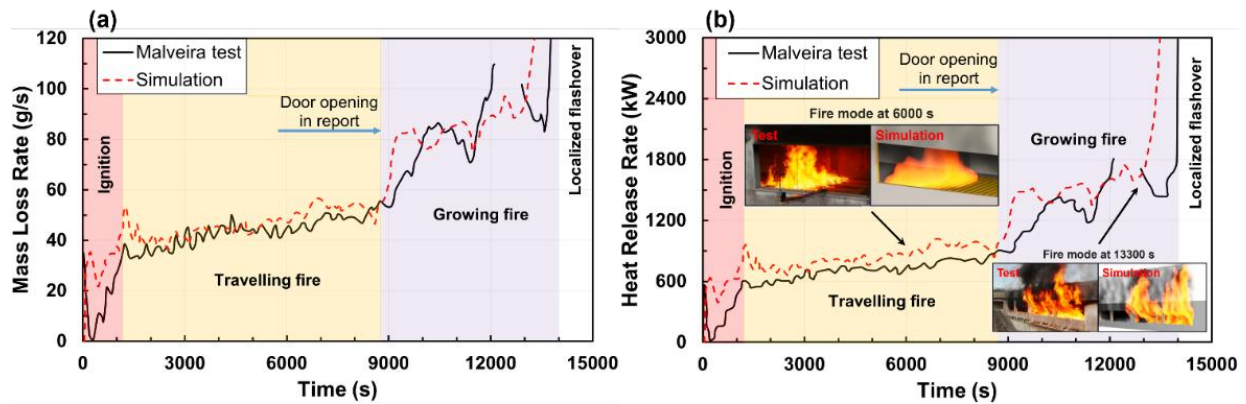


Fig. 5.4. Validation of the used model against the Malveira test [30] data: (a) MLR; (b) HRR.

5.3. Influence of compartment configuration factors on fire development

Modern large open-plan compartments can exhibit very different fire behaviors depending on certain design and fuel parameters. In this study, three key compartment configuration factors were examined: the ceiling beam arrangement (an inherent structural feature), the fuel load layout (a variable factor related to how combustibles are distributed), and the window opening height (an inherent ventilation parameter). These CFD simulations were unified under the central research question as shown in Fig. 5.5: How do compartment parameters, including fuel distribution, ignition location, ventilation height, and structural beam configuration, affect fire dynamics and the mitigation effectiveness of the timber-insulation mixed ceiling design? The following subsections present a parametric analysis of each factor (in the order of beam configuration, fuel layout, and opening height), using the validated CFD model of a large open-plan compartment with a timber-insulation mixed ceiling. This approach enables an assessment of how both inherent design features and variable fuel scenarios affect fire dynamics, and to identify potential strategies for fire mitigation in such compartments.

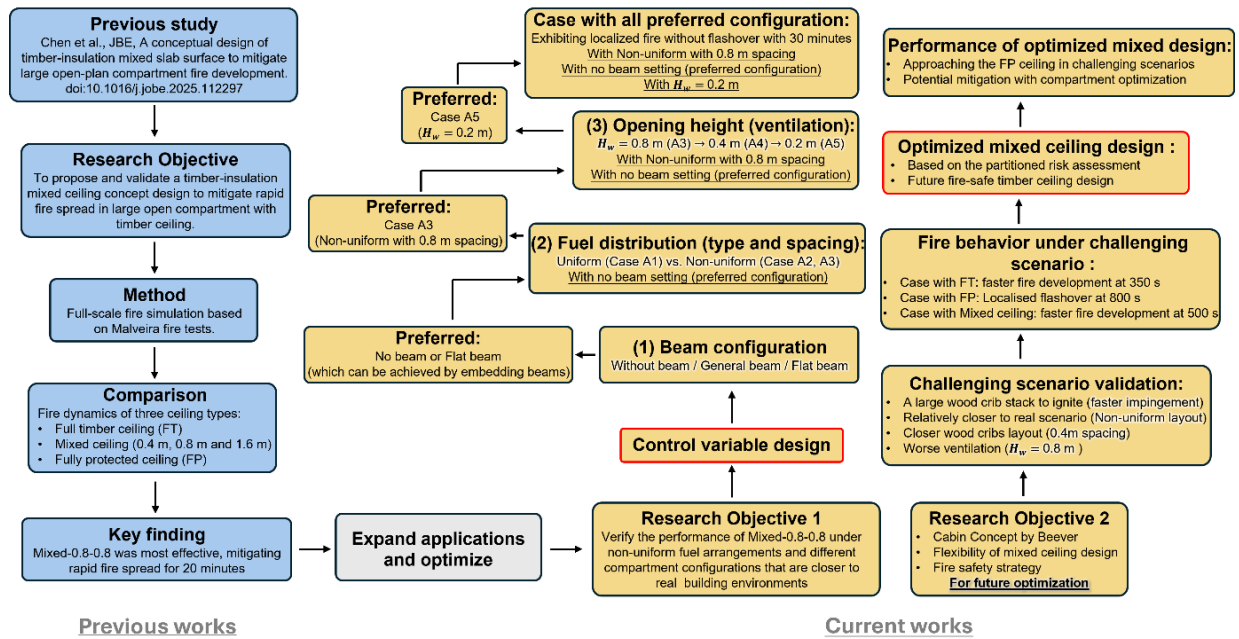


Fig. 5.5. Unified research questions as the framework for specific parameterization studies.

5.3.1. Effect of ceiling beam configuration

Large-span floor systems often require beams for structural support, but the presence of beams can alter compartment fire dynamics [112]. As illustrated in Fig. 5.6a, adding structural beams can help carry loads and reduce floor slab deflection or collapse risk under fire. However, combustible timber beams can add fuel to the fire, potentially intensifying its growth and prolonging its duration, while even non-combustible beams may obstruct the flow of hot gases and thereby change a fire's development pattern. It is therefore crucial to evaluate both the beneficial and adverse effects of ceiling beams on fire safety through

fire dynamics simulations. Building on those findings, a preliminary parametric study was conducted in this section to investigate how different beam configurations influence the fire in a mixed-ceiling compartment.

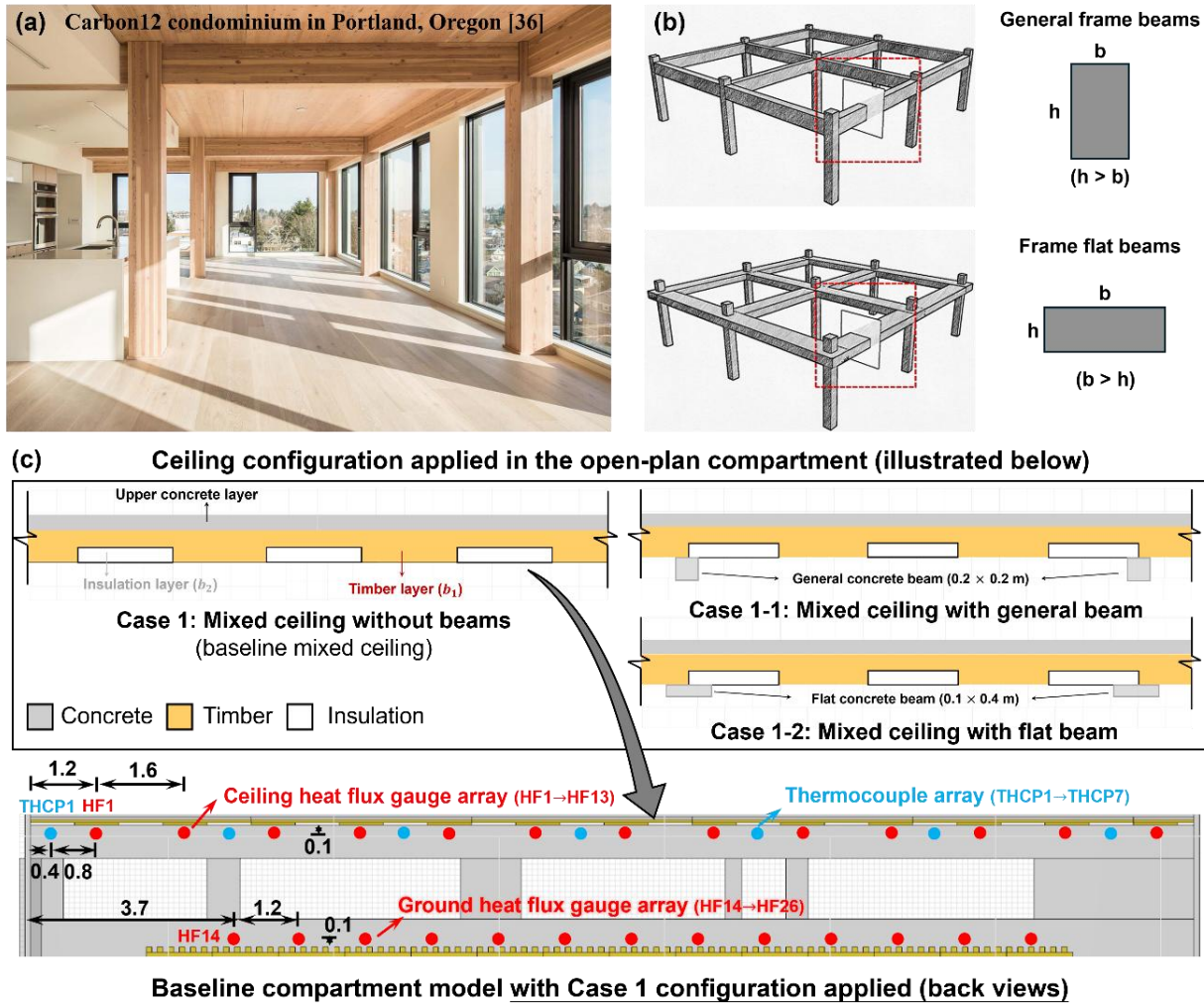


Fig. 5.6. Illustration: (a) A modern timber compartment with timber beams [148]; (b) Frame beam type options based on indoor clear height conditions, including the general and flat beam; (c) Case studies on the effect of beam configuration under mixed ceiling compartments.

Typically, beam setups based on compartment clear heights include normal framed beams (height $\geq$ width) and framed flat beams (width $>$ height), as shown in Fig. 5.6b. Subsequently, using the validated baseline model of the Malveira test compartment (with a mixed timber-insulation ceiling), three ceiling configurations were compared: one with no beam (Case 1), one with a deep general beam (Case 1-1), and one with a shallow flat beam (Case 1-2), as shown in Fig. 5.6c. The corresponding setup details are shown in Table 5.1. Both beam types were assumed to be non-combustible and are spaced at 4.0 m intervals across the entire 21.1 m width of the compartment. The general beam had a square cross-section 0.2 m $\times$ 0.2 m

(height $\geq$ width), representing a general deep frame beam, while the flat beam had a rectangular cross-section 0.1 m $\times$ 0.4 m (width $>$ height), representing a low-profile beam suited for height-restricted spaces. These beam dimensions in our current study are intentionally idealised for an initial sensitivity exploration and will be designed and improved in future work in accordance with typical structural design guidelines, including considering indicators such as the self-weight of the floor slab system, live loads, deflection standards and utilization rates. Apart from the beam addition, all other conditions (fuel load, ventilation, and the mixed ceiling design) were identical to the baseline scenario. This setup allowed us to isolate the effect of beam presence and shape on the compartment fire behavior.

Table 5.1. Summary of the setup of exploitation cases for different beam configuration and form.

Case No.	Type of fuel load distribution	Ceiling configurations		Beam configurations and form	Beam spacing
		Top layer	Bottom layer		
1				Without beam	/
1-1	Continuous & uniform	Concrete layer (0.05 m)	Timber-insulation mixed layer (0.10 m)	With general beam (Section size: 0.2 m $\times$ 0.2 m)	4.0 m
1-2				With flat beam (Section size: 0.1 m $\times$ 0.4 m)	

Lastly, to monitor the fire development under different layouts, instrumentation devices were embedded in the simulations, as shown in Fig. 5.6c. A grid of virtual thermocouples was arranged 0.1 m beneath the ceiling to record the gas temperature at various locations as the fire spread. Each thermocouple had a bead diameter of 1 mm with properties set to mimic real thermocouple behavior (emissivity 0.85, density 8655 kg/m³, specific heat 0.44 kJ/kg·K [119]), ensuring accurate capture of the hot gas temperatures. In addition, an array of gas-phase heat flux gauges was placed just below the timber strips of the mixed ceiling across the compartment to measure incident heat flux over time. Similarly, gas-phase heat flux gauge arrays were arranged near the ignition point with even spacing above the adjacent wood cribs at the ground ignition point, 0.1 m from the surface, enabling accurate measurement of ground-level heat flux and effective tracking of flame propagation across the fuel load arrangements. These instruments provided detailed data on how quickly the ceiling ignites, how the flame front travels, and the intensity of thermal feedback to the unignited fuels in each layout scenario.

5.3.1.1. Smoke flows and flame spread with and without beams

Fig. 5.7 illustrates the simulated fire development in the large open-plan compartment under three different beam configurations: no beam, general beam, and flat beam. In all CFD models presented in this chapter, the Very Large Eddy Simulation (VLES) mode employing an explicit predictor-corrector scheme

with second order accuracy in both space and time is activated to model the turbulence. The near-wall region was treated by means of the Smagorinsky form with the Van Driest damping function [149]. The grey-gas model was applied to estimate the radiative heat transfer, and its number of solid angles was increased to 200 (double the default value) to improve analysis precision. The presence and geometry of the beams influenced the local smoke dynamics and temperature distribution near the ignition region, consequently affecting the compartment fire behavior. Without beams, smoke freely rose to the ceiling and dispersed laterally with minimal obstruction, resulting in a uniform smoke layer and limited smoke stagnation or localized fire intensification. The introduction of a flat beam slightly obstructed horizontal smoke movement, forming small, localized smoke accumulation upstream but largely preserving smooth airflow without significant flame intensification beneath the beam. In contrast, the general beam caused notable disruption to the smoke flow.

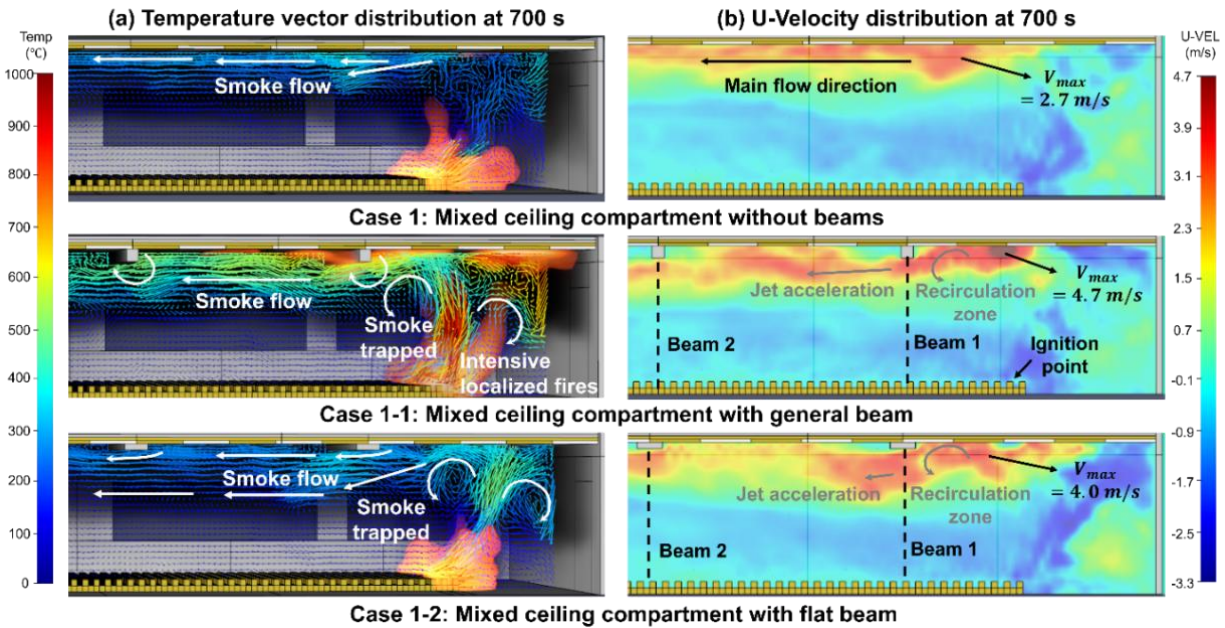


Fig. 5.7. Comparison of (a) smoke distribution and (b) airflow velocity fields at 700 s in compartments with different beam configurations under mixed ceiling strategy.

As shown in Fig. 5.7b, this deeper beam configuration acted as a substantial barrier, inducing a pronounced recirculation zone on its upstream side. Smoke trapped in this area recirculated and, upon overcoming the beam height, accelerated downstream, markedly enhancing local gas velocities and temperatures. This recirculation and jet acceleration phenomenon intensified localized fires in wood cribs on the ground by reinforcing thermal feedback, elevating the risk of early flame impingement on the ceiling and increasing the severity of localized burning. Therefore, the flat beam configuration emerges as advantageous, balancing structural requirements and fire safety by minimally impacting smoke movement and avoiding the severe fire intensification associated with deeper beams.

5.3.1.2. Fire growth indicators for different beam configurations

Based on the previous qualitative discussion, Fig. 5.8 presents a quantitative analysis to further illustrate the impact of beam configurations on fire development. Fig. 5.8a displays the incident heat flux evolution at ceiling level ($X = 2.8$ m) and ground level ($X = 3.7$ m) near the ignition area, highlighting the distinct moments when rapid fire growth commences under three beam setups. The presence of a general beam accelerates flame spread along the ceiling, causing earlier and more noticeable peaks in heat flux due to the beam's obstruction and associated gas acceleration phenomena. By 700 s, the Case 1-1 with general-beam configuration observed intense incident heat fluxes on compartment surfaces near the ignition, reaching levels sufficient to ignite the timber ceiling and wood cribs. Conversely, the no-beam and flat-beam scenarios exhibit delayed and comparatively moderate heat flux increases, demonstrating their effectiveness in mitigating rapid fire development.

Fig. 5.8b further illustrates the radiative heat flux distribution on compartment interior surfaces at the critical time of 700 s, clearly revealing the intensified localized fire development in the general-beam case, particularly near Beam 1 ($X = 4.0$ m). The noticeable radiation levels at this early-stage underscore how the deeper general beam configuration intensified thermal feedback to adjacent combustible materials. In contrast, scenarios without beams or with flat beams display substantially lower radiation, corroborating the observed slower progression of the fire. In addition, it is consistent with the results of a medium-sized test by Nothard et al. [112], which showed that the presence of beams below the exposed ceiling exacerbated localized heating and accelerated flame spread when compared to the no-beam case. These analyses reinforce the previous findings that appropriate beam design, such as a flat beam, reduces localized fire intensification risks in large compartments equipped with timber-insulation mixed ceilings.

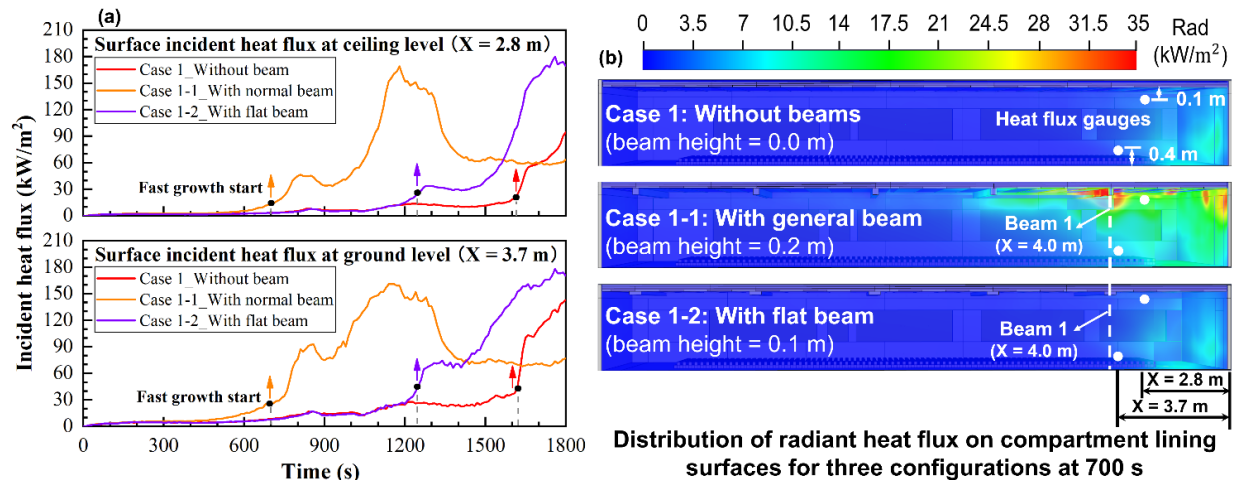


Fig. 5.8. Illustration: (a) Evolution of the incident heat flux on the ceiling and floor fuel surfaces of compartments in the area surrounding the ignition point; and (b) The distribution of radiative heat flux on compartment lined surfaces from opening opposite view at 700 s.

5.3.2. Effect of fuel load distribution (uniform vs. non-uniform)

Current full-scale fire tests involving large open compartments with timber ceilings generally assume continuous and uniformly distributed fuel loads [45, 141]. However, real building environments often feature non-uniform fuel distributions. Research by Nan et al. [46] investigating the effects of non-uniform fuel arrangements in well-ventilated spaces demonstrated that assuming uniform fuel distribution may underestimate the associated fire risks and recommended incorporating non-uniform fuel scenarios into performance-based fire safety designs. In response, the current study is the first to integrate non-uniform and discontinuous fuel load distributions into a CFD fire model for large open timber compartments. The primary objective is to comprehensively evaluate the effectiveness and robustness of the proposed timber-insulation mixed ceiling strategy under more challenging and demanding fire scenarios. It should be acknowledged, however, that despite incorporating non-uniform fuel layouts, the CFD modelling still cannot fully capture the stochastic variability of real-world fuel distributions, and further experimental validation and probabilistic modelling are needed to address this limitation.

5.3.2.1. Non-uniform fuel scenarios design

Based on the validated baseline model, which initially used a uniform array of wood cribs, a modified fuel arrangement was developed to represent a non-uniform fuel load. The original continuous uniform layout of wood cribs used in the Malveira test and baseline simulation, as shown in [Fig. 5.9a](#), was reorganized into a discontinuous, unevenly spaced configuration inspired by the Test 3 layout from Nan et al.'s experiments [46]. This new arrangement, illustrated in [Fig. 5.9b](#), maintains the same total volume of wood fuel as the uniform case but concentrates the cribs into clusters with clear gaps between them. It should be noted that this fixed-spacing cluster layout is an idealized alternative and does not claim to replicate the exact spatial distributions of combustibles in real buildings. Further research is required regarding cluster size, density, and spacing. Nan et al. [46] reported that in Test 3, flames from the second crib reached nearly 3.0 m high within two minutes of ignition, high enough to impinge on the ceiling of a typical compartment. By using a similar layout, a potentially more severe fire scenario without increasing the overall fuel load was simulated. In addition to this primary non-uniform layout, a further variant was created as shown in [Fig. 5.9c](#) to investigate the influence of combustible spacing on the fire: this variant uses the same non-uniform pattern but increases the separation distance between adjacent wood cribs. Apart from these changes in fuel positioning, all other simulation parameters including timber material properties, combustion kinetics, ventilation, and ignition source, were kept constant to isolate the effect of fuel distribution on the fire behavior. For all the fuel distribution cases analyzed, no ceiling beams were included in the model. This assumes a flat slab ceiling, which reflects common open-plan designs and also removes the beam influence so that the effects of the fuel layout can be observed more clearly.

To monitor the fire development under different fuel layouts, instrumentation devices were embedded in the simulations, as shown in Fig. 5.10. Similarly, a grid of virtual thermocouples and an array of gas-phase heat flux gauges with the same characteristics are set 0.1m below the ceiling surface.

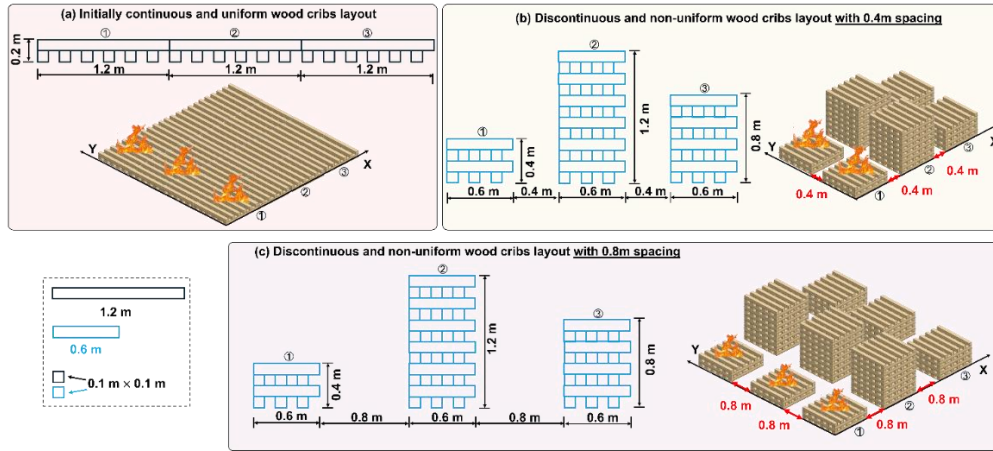


Fig. 5.9. Schematic of fuel load set up for each simulation (partial).

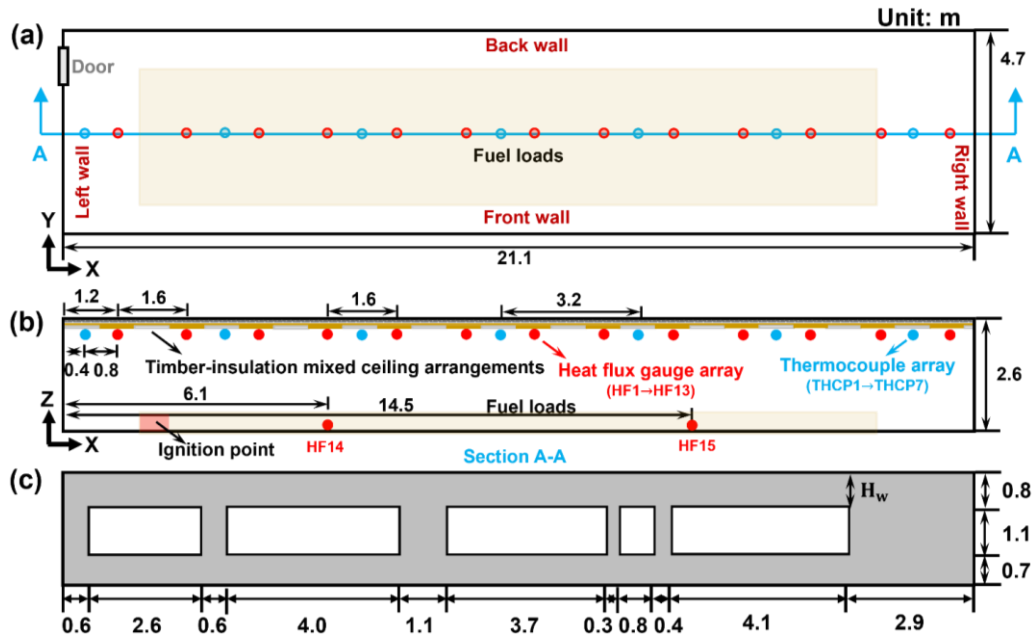


Fig. 5.10. Fire simulation model for case studies on non-uniform fuel load inside compartment with timber-insulation mixed ceiling: (a) Layout of the compartment; (b) Section A-A; (c) Front view.

5.3.2.2. Uniform vs. non-uniform fuel load - fire behavior

Using the above setups, two baseline scenarios with identical total fuel load but different spatial arrangements were compared: Case A1 with a continuous, uniformly distributed wood crib array representing a traditional design assumption, and Case A2 with a discontinuous, non-uniform crib arrangement representing a challenging clustered fuel scenario. The key parameters distinguishing these

cases are summarized in Table 5.2. The simulations revealed markedly different fire dynamics between the uniform and non-uniform layouts. A side-by-side comparison of the fire progression in these two cases is shown in Fig. 5.11.

Table 5.2. Summary of the setup of exploitation cases for fuel load distribution.

Case No.	Type of fuel load distribution	Spacing between wood crib (m)	Distance from the top edge of windows to the ceiling H_w (m)
A1	Continuous & uniform (C&U)	/	0.8
A2	Discontinuous & non-uniform (D&N)	0.4	

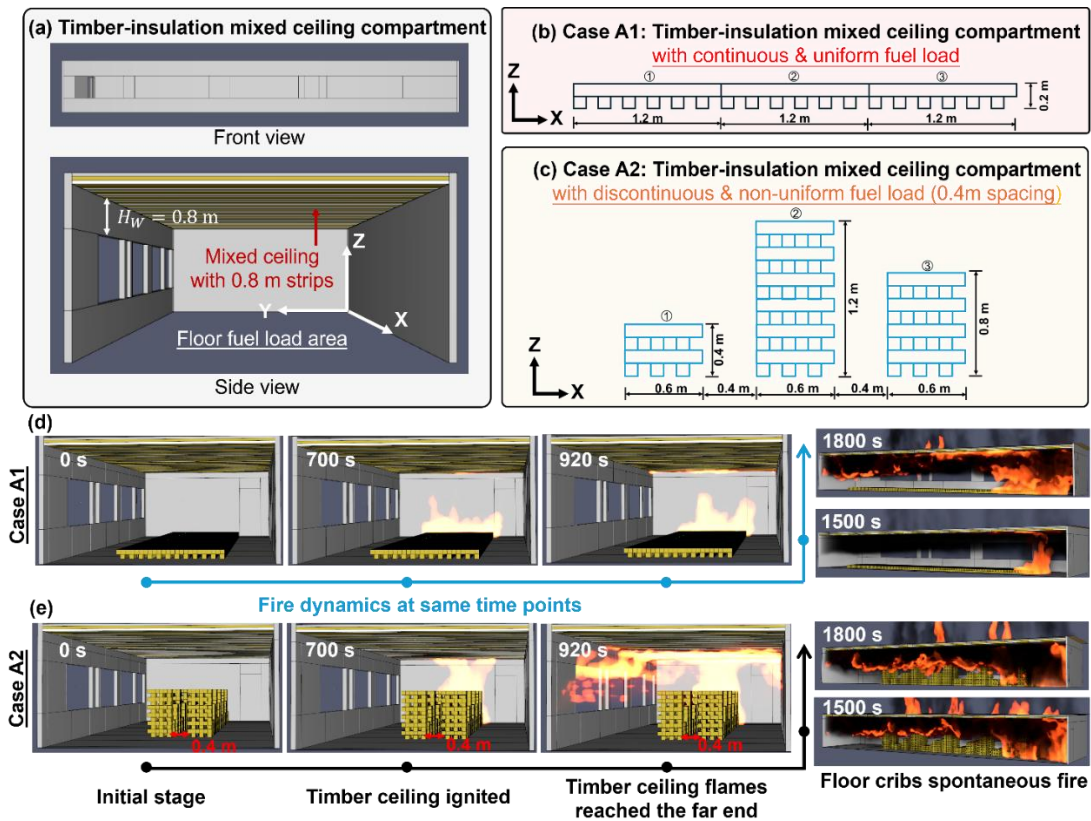


Fig. 5.11. Illustration: (a) Compartment models built-up in CFD simulation; (b) (c) Two different fuel load pattern for comparison; (d) (e) Fire behavior of large open compartment with timber-insulation mixed ceiling corresponding to two fuel loads.

In the non-uniform case (Case A2), the clustered wood cribs led to the formation of strong, localized plumes early in the fire. Within 700 s of ignition, one of these plumes impinged on the ceiling, causing the timber strips of the mixed ceiling to ignite near the flame impingement area. By around 920 s, the ceiling fire in Case A2 had spread across the majority of the compartment's ceiling, creating a continuous flame front beneath the ceiling. This intense ceiling burning, combined with the radiation from the flames, then

led to ignition of the remaining wood cribs on the floor by approximately 1500 s. In contrast, the uniform fuel case (Case A1) exhibited a slower and more contained fire development. Although the ceiling in Case A1 also began to ignite around 700 s (the first ceiling ignition was observed at the location above the fire source), the burning remained localized and weak at that time. By 920 s, some flame spread along the ceiling was evident in Case A1, but the presence of the alternating insulation strips in the mixed ceiling limited the preheating of adjacent timber sections as previously demonstrated in [143]. This meant that the ceiling flame did not immediately jump to neighbouring timber strips. A continuous flaming zone across the ceiling did not establish until roughly 1500 s in the uniform case. Even then, the fire intensity in Case A1 was noticeably lower than in Case A2, full involvement of both ceiling and floor fuels was only observed by around 1800 s for the uniform layout, and the heat release rate and temperatures were lower at comparable times. These findings, observed within the context of the current study on compartments with a timber-insulation mixed ceiling, demonstrate that treating the fuel load as uniformly distributed, as commonly adopted in previous experimental setups, may lead to a significant underestimation of the speed and intensity of fire growth under comparable conditions. Specifically, the non-uniform fuel layout used here resulted in more rapid fire spread and higher peak burning intensity within this compartment configuration, highlighting the importance of considering non-uniform fuel distributions in fire safety assessments for large compartments with exposed or partially exposed combustible ceilings. However, the specific outcome remains dependent on detailed configuration factors, such as whether the ceiling material is combustible.

5.3.2.3. Effect of fuel spacing in a non-uniform fuel layout

The influence of crib spacing was investigated by comparing Case A2 (the baseline non-uniform layout with relatively tight spacing) against Case A3, a modified non-uniform layout with increased separation between crib groups. In Case A2, the side-to-side gap between adjacent cribs was 0.4 m, whereas in Case A3 this gap was doubled to 0.8 m as shown in [Table 5.3](#). Increasing the spacing in this way, while maintaining the total fuel mass and arrangement pattern, required adjusting the layout such that the number of crib rows across the compartment width increased from two to three to accommodate the dispersed fuel.

[Fig. 5.12](#) compares the fire development for these two spacing scenarios. At the closer 0.4 m spacing (Case A2), the adjacent cribs were near enough that flames and the intense thermal radiation from an ignited crib could readily ignite its neighbor. Essentially, once one crib became fully involved, the heat feedback of convective and radiative processes to the next crib was sufficient to rapidly spread the fire from one cluster to the next. This led to a fast flame spread both along the floor and upward: a continuous flame plume reached the ceiling by about 700 s, and by 920 s a large portion of the ceiling was on fire. The burning of the ceiling then further enhanced the thermal radiation back down to the floor, so the remaining fuel on the ground became involved by around 1500 s, resulting in a very intense fire that covered almost the entire

compartment. In contrast, at the wider 0.8 m spacing (Case A3), the separation between crib groups acted as a buffer. The wider gap greatly reduced the radiative heat transfer between burning and unignited cribs, increasing the time required for flames to spread from one crib to the next. As a result, the spread of the fire was slowed. The fire in Case A3 remained more compartmentalized and dispersed: ceiling ignition was delayed, and even when parts of the ceiling did ignite, the heat release rates throughout the simulation were lower than those in the tightly spaced case. Overall, fire development with the 0.8 m spacing was much less aggressive, with prolonged burning of isolated cribs rather than one rapidly merging fire. These results highlight the sensitivity of non-uniform fuel arrangements to the spacing of fuel elements. An increase in clear space between combustibles can markedly mitigate the fire spread rate in a large compartment, suggesting that maintaining sufficient gaps in fuel layout (where possible in practice) may help to mitigate fast fire propagation in open-plan spaces.

Table 5.3. Summary of the setup of exploitation cases for fuel spacing under non-uniform fuel load.

Case No.	Type of fuel load distribution	Spacing between wood crib (m)	Distance from the top edge of windows to the ceiling H_w (m)
A2	Discontinuous & non-uniform	0.4	0.8
A3	(D&N)	0.8	

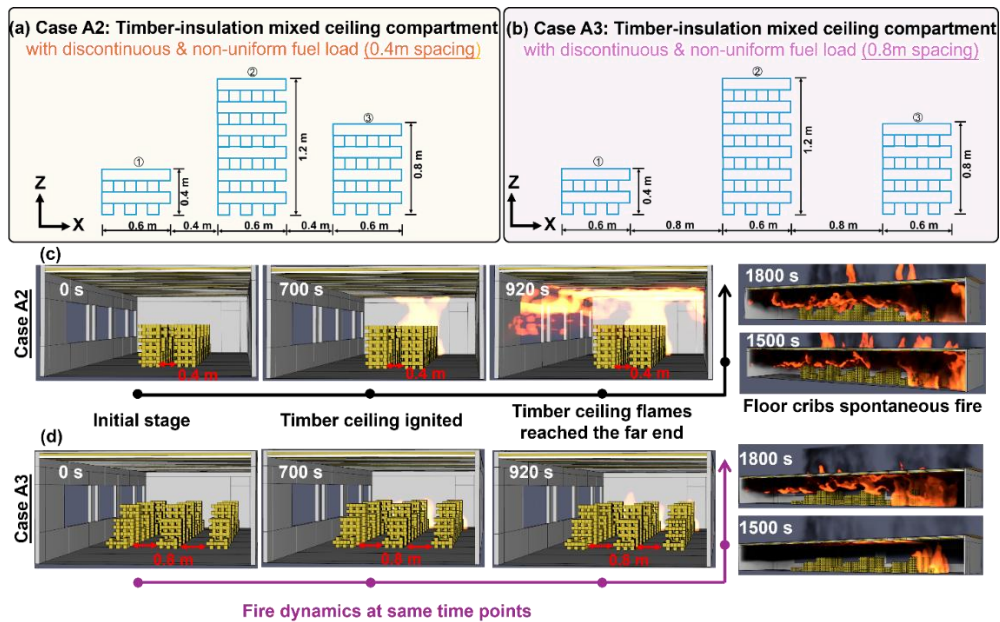


Fig. 5.12. Discontinuous & non-uniform fuel load patterns for large open compartment with timber-insulation mixed ceiling: (a) 0.4 m spacing; (b) 0.8 m spacing; (c) (d) Corresponding fire behaviors.

5.3.2.4. Combined analysis of implication of fuel distribution

A quantitative comparison of the different fuel distribution cases (uniform vs. non-uniform, and varying spacing) is presented in Fig. 5.13 and Fig. 5.14. Despite all cases having the same total fuel load

and the same ventilation and ignition conditions, the temperature evolutions and burning rates differ due to the layout. Fig. 5.13a plots the compartment adiabatic surface temperatures (AST) near the ceiling at 700 s and 920 s for the three representative cases: uniform (Case A1), non-uniform dense (Case A2), and non-uniform wider-spaced (Case A3). The Case A2 with the dense non-uniform layout clearly produces a much higher upper-layer temperature in the compartment at those times compared to the uniform Case A1. This reflects the formation of a pronounced high-temperature plume zone above the ignition region in A2, which is driving the rapid fire spread. Consistently, the ceiling thermocouple data in Fig. 5.13b show that in Case A2, the thermocouples at various distances from the ignition point reach 450 °C earlier than in Case A1, indicating a faster spread of the ceiling flame front in the non-uniform scenario. This threshold aligns with the typical piloted ignition temperature range of wood (400 - 450 °C) [150] and corresponds to temperatures commonly observed at the leading edge of spreading flames under similar fire conditions [151]. On the other hand, the non-uniform with wider spacing of Case A3 resulted in clearly lower temperatures at 700 s and 920 s, almost half of those in Case A2 at some locations, which suggests that the flame spread and its radiative heating of the compartment were greatly inhibited in the early stages of the fire. In Case A3, the ceiling thermocouples record a much slower temperature rise, and some thermocouples away from the ignition point reached 450 °C until 1500 s, almost the end of the simulation.

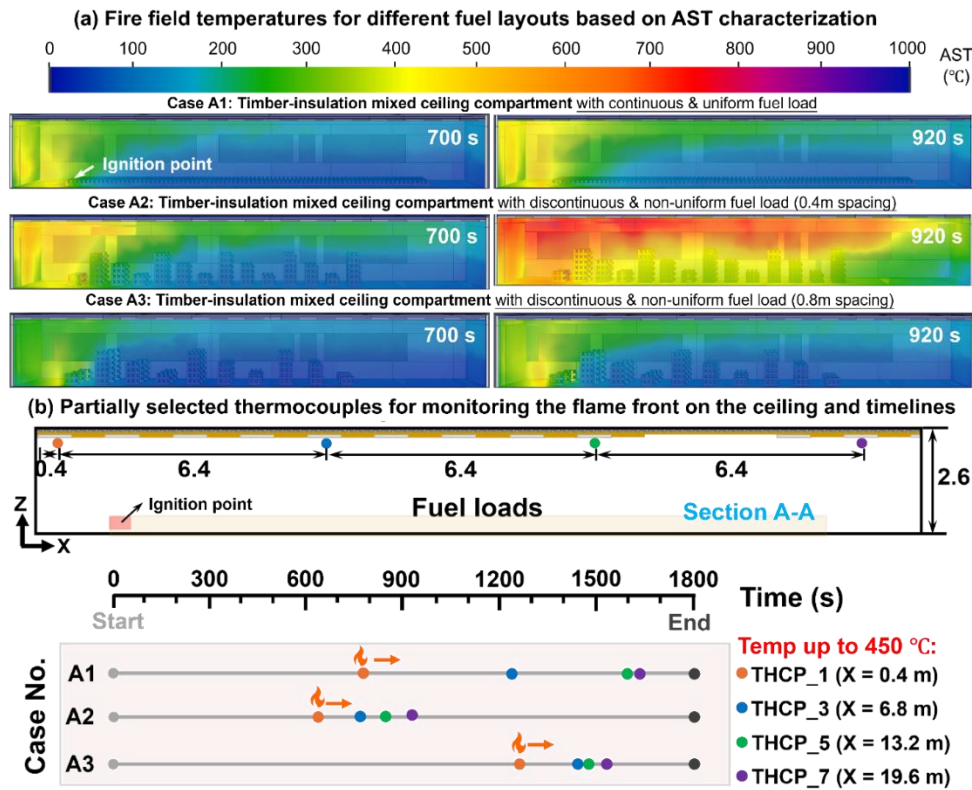


Fig. 5.13. Illustration: (a) Fire field temperature based on AST (Adiabatic Surface Temperature); (b) Timeline of preset thermocouples characterizing the development of the ceiling flame front.

Fig. 5.14a further shows the time evolution of upper-layer gas temperatures at several positions ($X = 5\text{ m}$, 10 m , 15 m) for Cases A1–A3. Initially, all scenarios exhibit gradual temperature rises. However, noticeable changes appear as the fire intensifies near the ignition region. Specifically, Case A2, featuring densely arranged fuels, shows rapid and significant temperature increases at all measurement points by 700 s, indicating rapid flame spread and accelerated fire growth. Conversely, Case A3, characterized by a more dispersed fuel arrangement, delays the onset of rapid-fire growth by roughly 13 minutes, illustrating how clear combustible spacing can be effective in mitigating the development of an intense fire. The uniform fuel distribution (Case A1) further delays the rapid temperature rise by approximately 15 minutes, indicating that only considering uniform fuel distribution may not capture the high temperature areas in some fire scenarios, and may lead to optimistic judgments on the severity of the fire. Fig. 5.14b complements these observations by presenting and comparing the mass loss rate (MLR) ratios of the ceiling timber at critical times identified in Fig. 5.14a. The results clearly demonstrate a increased ceiling timber pyrolysis ratio in Case A2 starting from 700 s, aligning closely with the rapid temperature elevations recorded. This intensified timber pyrolysis indicates extensive ceiling timber involvement in combustion, reinforcing the elevated fire risk inherent to dense, non-uniform fuel arrangements. In comparison, the More discrete fuel arrangements in Case A3 exhibit similar timber pyrolysis ratios as the uniform distribution in Case A1, and even perform better in the early stages, validating the effectiveness of clear fuel spacing in mitigating rapid fire spread and improving overall fire safety performance.

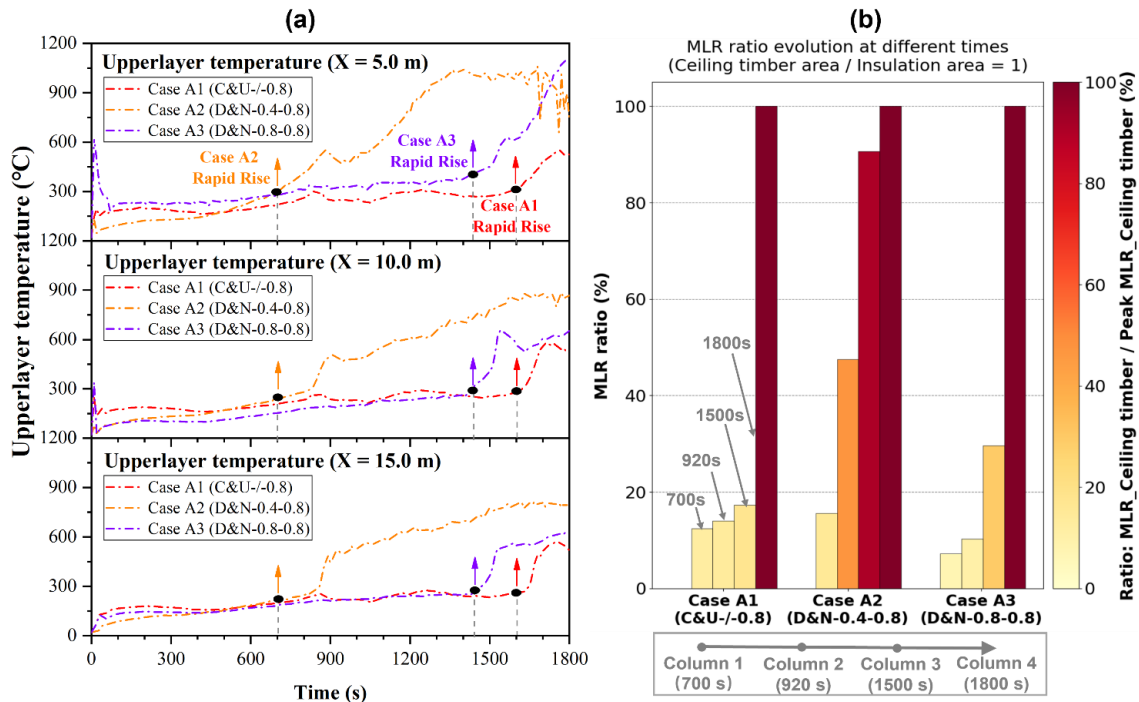


Fig. 5.14. Illustration: (a) Evolution of temperature layers at 5, 10, and 15 m along the length of the compartment and (b) Histogram of fuel distribution versus the ratio of MLR of ceiling timber.

Fig. 5.15 compares the heat release rate (HRR) and floor incident heat flux for these cases. From these quantitative measures, it is evident that Case A2 (non-uniform, tightly spaced fuel) produces the most severe fire dynamics with higher peak temperatures, faster burning rates, and greater floor heat flux, while Case A1 (uniform) is the least severe, with Case A3 (non-uniform, widely spaced) in between. For instance, the peak HRR in Case A2 is greater and occurs sooner than in the other cases, whereas Case A3 shows a noticeably lower HRR curve, with a delayed and reduced peak due to the inhibited flame spread as shown in Fig. 5.15a.

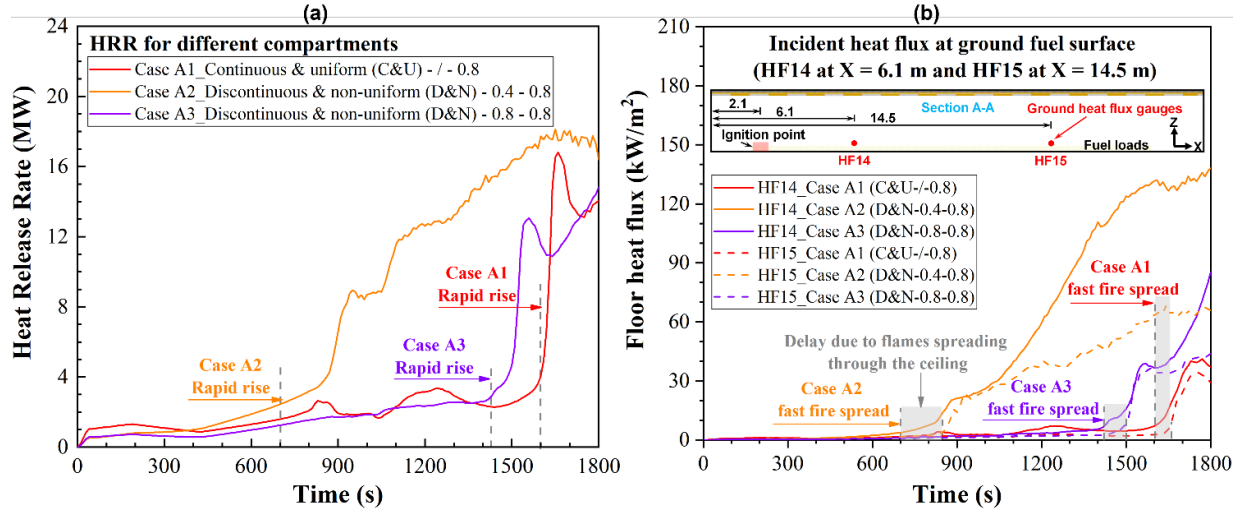


Fig. 5.15. Illustration: (a) Evolution of compartment heat release rate and (b) floor incident heat fluxes by HF14 and HF15 under three fuel-distribution configurations (Cases A1–A3).

In summary, even if the initial fuel load densities are the same and there is the potential for rapid localized fire development and spread, the pattern of fuel arrangement has implications for the results. A rational optimization of the fuel layout, specifically using a discontinuous, well-spaced arrangement, in combination with the mixed-ceiling design, can effectively delay fire development and reduce its intensity. These findings underscore the value of examining varied fuel distributions, including clustering and spacing effects, in fire modelling for large compartments with combustible ceilings. While uniform fuel layouts remain a useful and conservative approach in many design scenarios, they may not consistently capture more rapid-fire growth patterns that can arise under certain non-uniform conditions. Conversely, fuel arrangements recommended after extensive parameter analysis may serve as a potential strategy for mitigating fire hazards in practice, though further research is needed to establish the design fire scenarios that closely resembles a real fire.

5.3.3. Effect of window opening height (ventilation configuration)

The vertical position of openings such as windows in a compartment is another critical factor that can influence fire dynamics by affecting smoke ventilation. In the scenarios analyzed above, it was observed

that the accumulation of a hot smoke layer under the ceiling prior to ceiling ignition played a key role in driving the fire spread, the trapped hot gases preheated the timber ceiling and intensified the localized fire growth. This suggests that enhancing smoke exhaust at high levels could be a potential strategy to mitigate fire spread. Therefore, the distance from the top of the window to the ceiling with the fire development was investigated, as an additional parameter. In practical terms, this corresponds to evaluating different window head heights, a form of passive design measure to improve ventilation of hot smoke. The mixed timber–insulation ceiling strategy was maintained in all cases.

5.3.3.1. Scenario setup for opening heights

Starting with Case A3 featuring the widely spaced non-uniform fuel scenario, which has the best optimization potential with the use of mixed ceilings, the height of the window openings was changed while keeping the fuel layout and all other conditions constant, including the ventilation area. In Case A3, the top of the window opening was 0.8 m below the ceiling, which is considered a lower opening since there is a larger smoke reservoir. Two additional cases were considered: Case A4 with the window top 0.4 m below the ceiling (a moderately high opening), and Case A5 with the window top just 0.2 m below the ceiling (a high opening, very close to the ceiling). These values are summarized in [Table 5.4](#). By examining these three configurations, the goal was to understand how increasing the effective opening height (i.e., improving the compartment’s vertical ventilation) would interact with the mixed ceiling design in terms of smoke accumulation, flame spread, and overall fire growth.

Table 5.4. Summary of the setup of exploitation cases for window opening height.

Case No.	Type of fuel load distribution	Spacing between wood cribs (m)	Distance from the top edge of windows to the ceiling H_w (m)
A3	Discontinuous & non-uniform	0.8	0.8
A4			0.4
A5			0.2

5.3.3.2. Influence on smoke accumulation and fire spread

The simulation results in [Fig. 5.16](#) show that the window opening height has a significant impact on the compartment’s smoke exhaust efficiency and thus on the fire’s progression. To isolate the effect of the opening height on smoke exhaustion and fire dynamics, the total windows opening area was kept constant across Cases A3, A4, and A5. Only the vertical position of the window openings was changed by shifting the top edge closer to the ceiling, thereby reducing the soffit height (H_w) from 0.8 m (Case A3) to 0.4 m (Case A4) and 0.2 m (Case A5), respectively. In the case of the lowest opening (Case A3, 0.8 m gap), the windows are positioned relatively far below the ceiling, meaning hot smoke had to accumulate to a deeper layer before it could begin to flow out of the compartment. Consequently, in the early stages of the fire, smoke and heat built up rapidly under the ceiling. This led to an expansion of the hot smoke layer (a hot

zone) downward from the ceiling and thermal feedback to the ceiling near the fire origin. The preheating of the timber ceiling by this accumulated smoke caused the ceiling flames to spread faster and contributed to a quicker rise in the heat release rate. In contrast, with a medium-height opening (Case A4, 0.4 m gap), the buildup of the hot smoke layer was slowed, heat was vented earlier. The fire spread to adjacent fuel and the growth of the hot layer were delayed relative to Case A3. For the highest opening (Case A5, 0.2 m gap), the window openings were almost at ceiling level, allowing hot gases vent almost immediately. However, the improvement from the medium to the highest opening was not as significant as the improvement from low to medium, in other words, Case A5 did exhaust smoke more effectively than Case A4, but with somewhat diminishing returns. Overall, the trend is clear: higher window openings (smaller gap to the ceiling) lead to more efficient removal of hot smoke, which in turn mitigates the rate and extent of fire spread. By appropriate design of the opening height in conjunction with the mixed ceiling, the development of the fire can be effectively slowed and controlled.

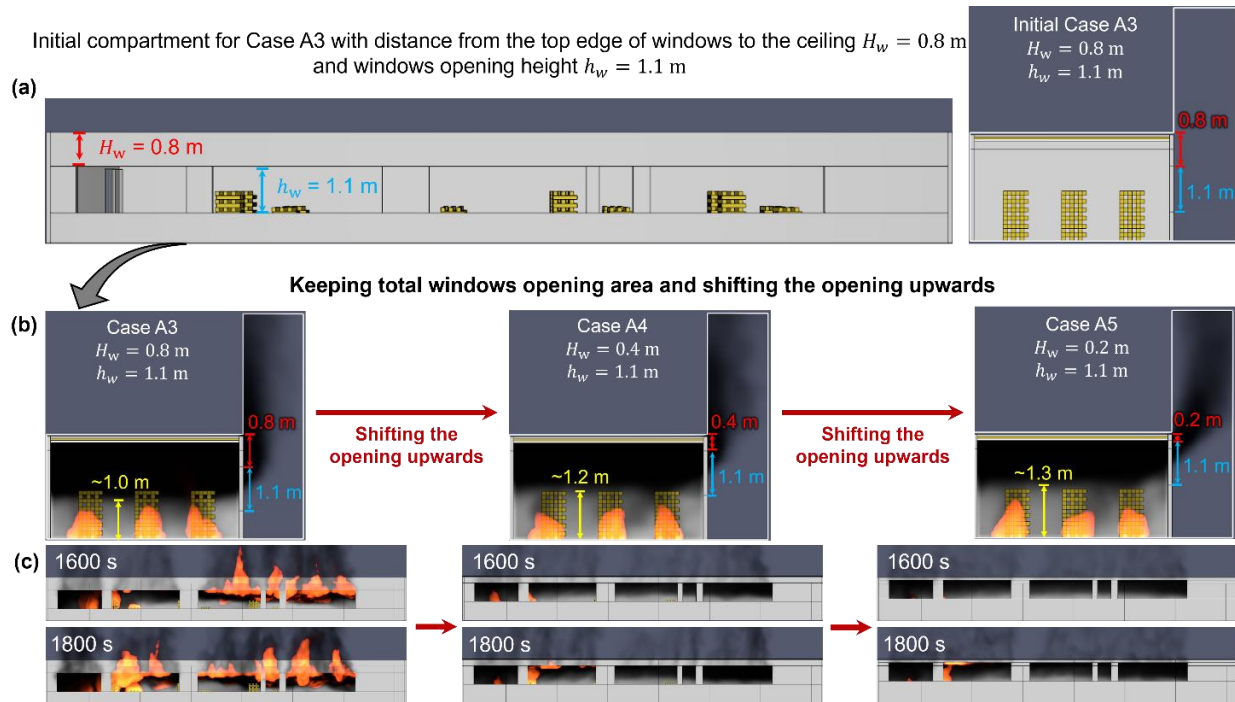


Fig. 5.16. Schematic illustration: (a) (b) Smoke accumulation inside compartments with different opening heights; (c) Fire development inside compartment at different opening heights.

5.3.3.3. Fire dynamics for different opening heights

A more detailed comparison of the fire dynamics metrics for the three opening heights was provided in Fig. 5.17. In Case A3 (low openings), the limited smoke exhaust led to a continuous accumulation of hot gases under the ceiling. By around 1500 s, this resulted in a sharp increase in the compartment heat release rate, essentially a phase of rapid compartment fire development due to the sustained ceiling flame spread

and the subsequent involvement of a large area of ceiling and floor fuels. Correspondingly, a sudden increase in the incident heat flux to the floor was observed at this time (for example, the heat flux gauges at $X = 6.1$ m and $X = 14.5$ m recorded rapid increases), indicating that the large, continuous ceiling fire in Case A3 was strongly radiating heat downwards and intensifying the burning of the fuel on the floor. In Cases A4 and A5 (higher openings), this scenario was notably different. As shown in Fig. 5.17a, the HRR in Cases A4 and A5 increased more gradually and remained lower than in Case A3, and the floor heat fluxes were also much more moderate, indicating that the fire spread was restrained. Fig. 5.17b plots the smoke volume flow rate through one of the windows, opening 1. For Case A4 and A5, the smoke flow increases steadily from early in the fire, whereas in A3 the flow is limited early on. Among the cases, Case A5 (0.2 m gap) provided the best smoke exhaust performance with the window openings closest to the ceiling, so the compartment maintained the lowest overall temperatures and heat fluxes throughout the fire. It should be noted that raising only the top edge of the window, while keeping the total opening area constant, is a conceptual approach adopted in this study to isolate the effect of smoke layer height. In real architectural practice, however, lower edge of the window heights is most likely fixed, and increasing the opening height would typically require a larger glazed area. In summary, elevating the window opening height (i.e. placing openings higher on the wall, nearer to the ceiling) has a clear beneficial effect on fire development in large compartments with a mixed ceiling.

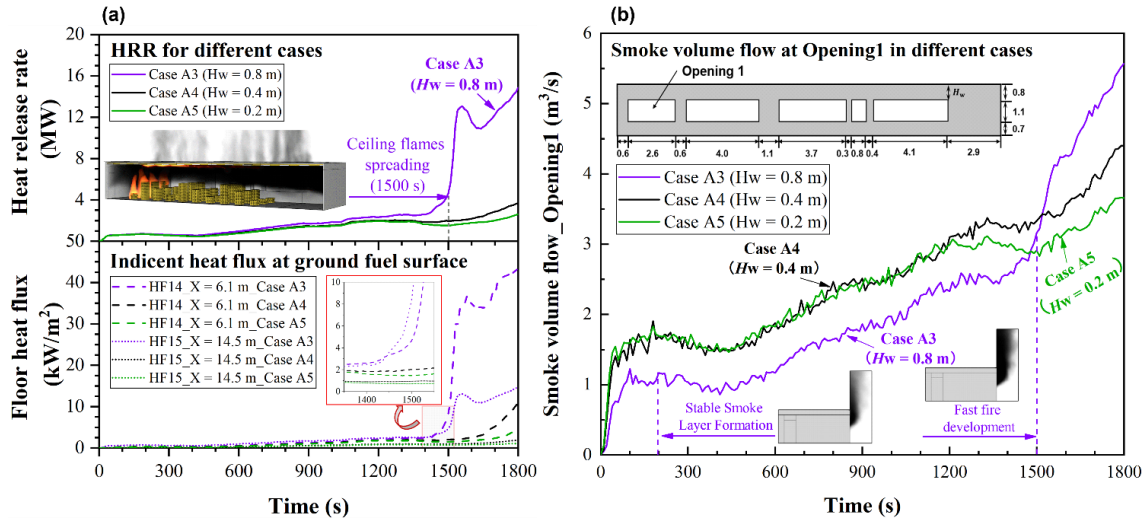


Fig. 5.17. Effect of fuel distribution on fire characteristics: (a) HRR and floor heat flux; (b) Smoke volume flow at the opening 1.

5.4. Performance discussion of timber-insulation mixed ceiling and future optimization

5.4.1. Performance comparison against a challenging fire scenario of high fire load density

To demonstrate the applicability of the mixed ceiling strategy in a comparative manner, a full-timber ceiling (FT) design and a full-protection ceiling (FP) design are given as the upper limit and the lower limit

in terms of ceiling combustibility, as shown in Fig. 5.18a. The compartment setup is largely identical to the previous numerical simulation cases while discussing the factors such as beam settings, fuel arrangement, and opening heights. Particularly, the comparative cases in this section adopt a challenging fire scenario by selecting a large wood crib stack to ignite. As shown in Fig. 5.18b, the wood crib bed is non-uniformly distributed (average fuel load density remains 420 MJ/m^2) and the spacing is 0.4 m , which leads to a large fire at early stage and potentially cause very fast fire spread in this large compartment. It should be noted that no beam is assumed in the comparative cases, which allows faster smoke spread at the early stage of fire but also weakens the earlier hot smoke accumulation above the fire source. By comparing the simulation results with those of a full-timber ceiling (FT) and a full-protection ceiling (FP) under the same conditions, the strengths and potential weaknesses of the mixed-ceiling strategy under this challenging initial fire scenario can be evaluated.

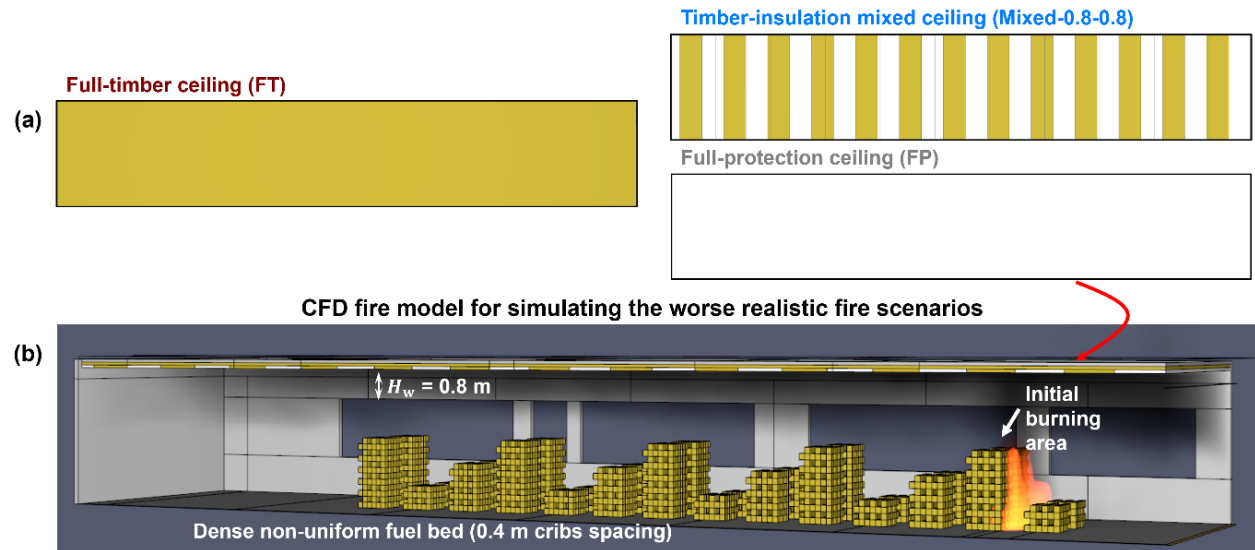


Fig. 5.18. Performance of timber-insulation mixed ceiling in a challenging fire scenario: (a) Different ceiling designs for the reference compartment; (b) illustration of long compartment model with wood crib stacks at floor.

As shown in Fig. 5.19, in the case of the full timber ceiling (FT), the ceiling slab was ignited only 200 s after the fire started, followed by rapid flame spread along the combustible surface. The ceiling flames reached the far end of the compartment by 350 s, and the entire floor fuel was fully involved by 500 s. Under the same challenging fire scenario, the full-protection ceiling (FP), being completely non-combustible, prevented faster ceiling fire spread. However, the intense and concentrated fuel combustion still led to a localized flashover by 800 s, indicating that even a fully protected ceiling cannot always characterize travelling fire behavior under this challenging fire scenario. The mixed ceiling (Mixed-0.8-0.8) demonstrated early-stage fire mitigation, closely resembling the FP case until approximately 400 s. It exhibited a clear mitigation effect similar to the FP case, delaying the ignition of ceiling timber strip.

Although the exposed timber strips eventually contributed to fire growth in later stages, resulting in faster development than in the FP case, the initial delay provided by the mixed ceiling remains valuable for enhancing escape and rescue time in the critical early phase of the fire.

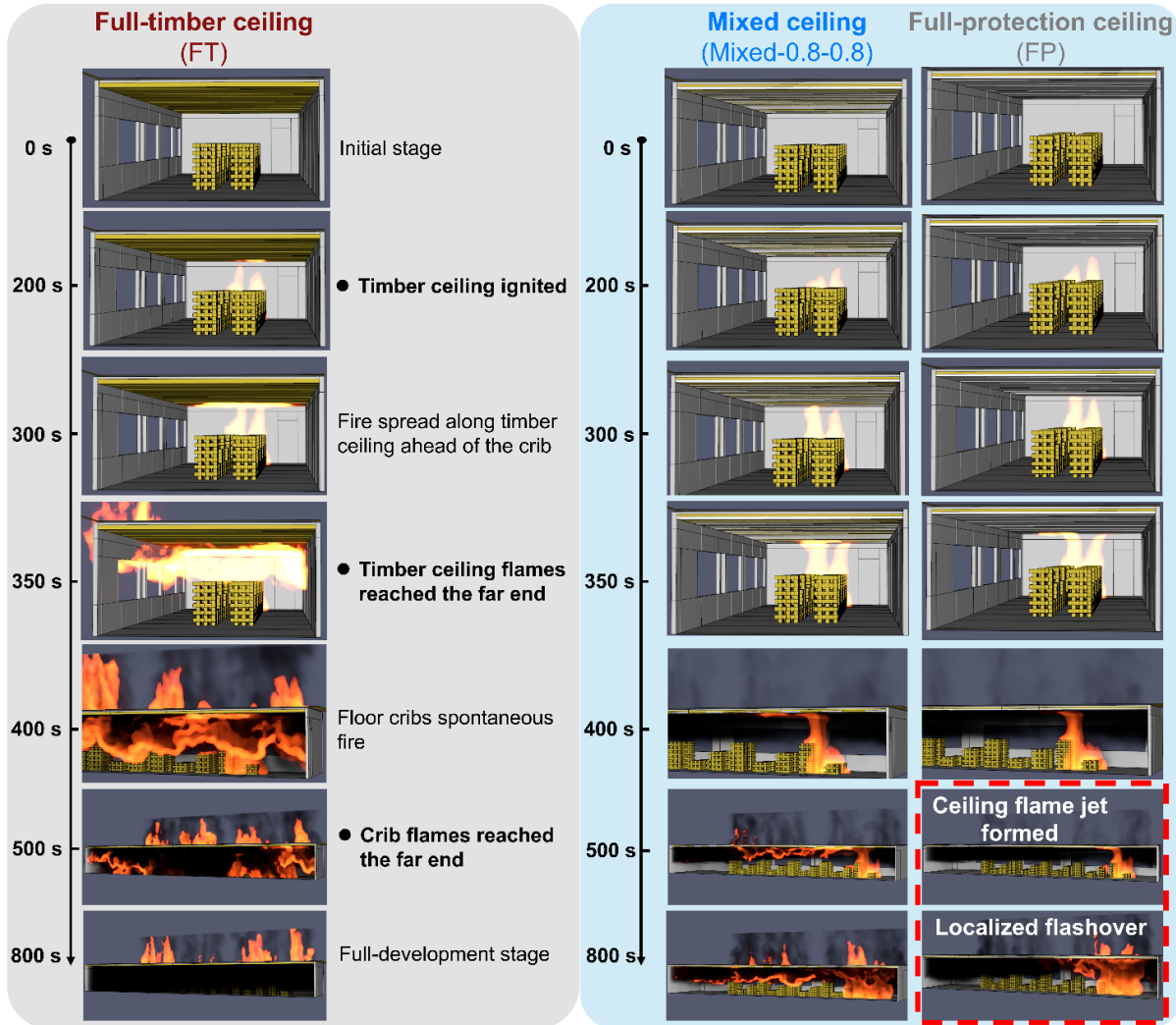


Fig. 5.19. Visual results from CFD fire models with different ceiling under the worst real fire scenario (interior and back views).

5.4.2. Zonal optimization of mixed ceiling design as a vision of future fire-safe timber ceiling design

Recognizing the inherent flexibility of the timber-insulation mixed ceiling design, a further optimization based on the principle of partitioned protection may be possible in future buildings. As the “Cabin Concept” [152] in public transportation buildings (e.g., airports) tends to install high fire protection measures in high-risk zones (shops), while placing minimal fire protection measures in low-risk zones (e.g., departure halls). In a large compartment of different use functions, it may be possible to adopt various levels of mixed-strip design corresponding to the floor fuel distributions. Specifically, the mixed ceiling was partitioned into areas reflecting different risk levels: fully protected by non-combustible insulation in high-

risk zones, regular mixed timber-insulation design in medium-risk zones, and fully timber ceilings complemented by passive fire protection systems such as sprinklers in low-risk zones. Fig. 5.20 illustrates this explorative design flow for optimizing the proposed mixed ceiling configurations, aiming to enhance fire mitigation under extreme scenarios. It should be noted that the optimized case using the zonal design (T50P50Z) maintains the same ratio of timber and insulation strips as the original design for the mixed ceiling case, i.e., 50% of timber surface and 50% of protection surface.

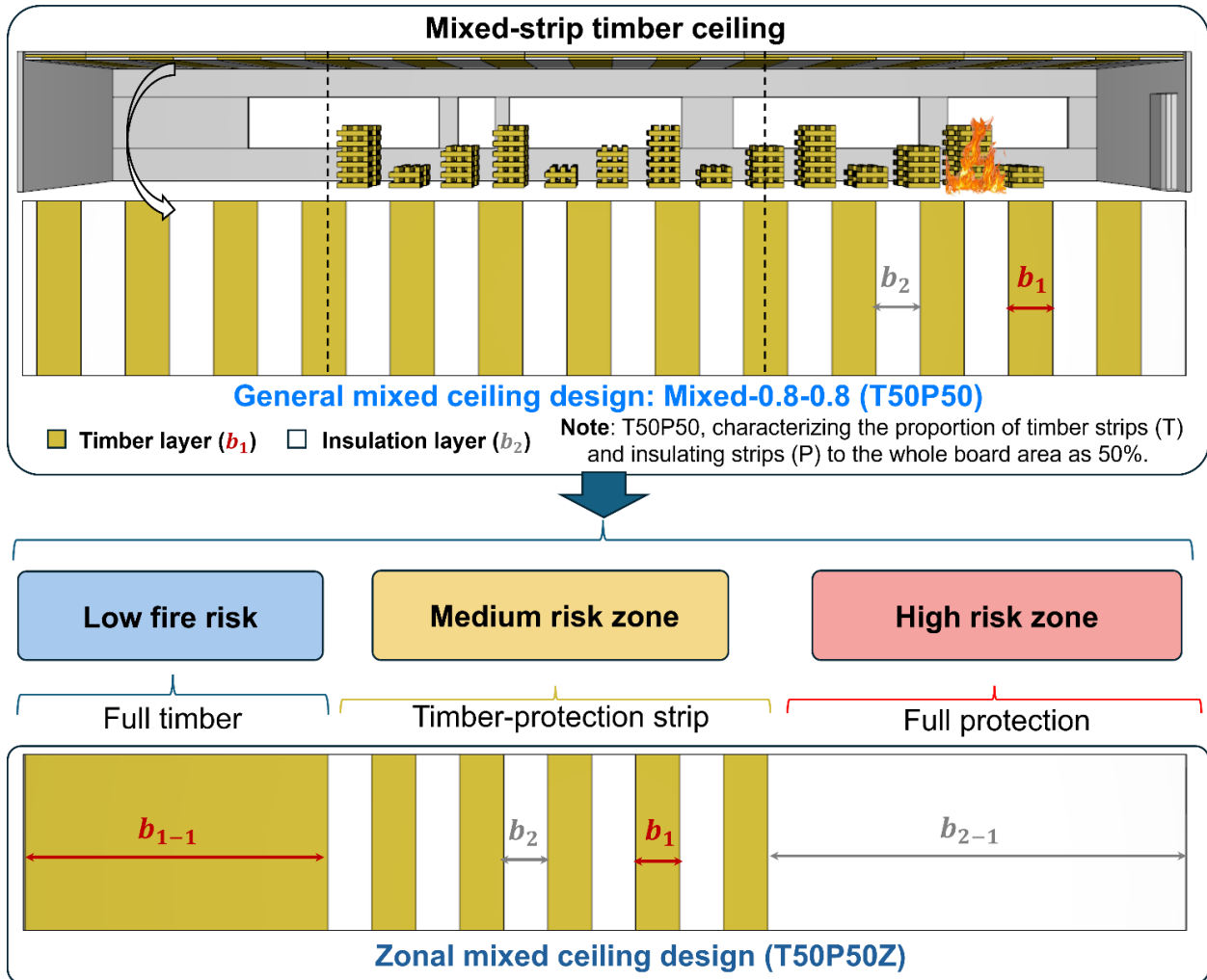


Fig. 5.20. Illustration of optimized mixed ceiling design based on the partitioned risk assessment.

The effectiveness of this optimized design (T50P50Z) is quantitatively assessed in Fig. 5.21, where it is compared against both the original mixed ceiling (Case Mixed-0.8-0.8(T50P50)), a fully timber ceiling scenario (Case FT) and a fully non-combustible protection scenario (Case FP). While the original mixed ceiling configuration mitigated fire spread in the early stages compared to the fully timber ceiling, its effectiveness was limited. In contrast, the optimized design based on the partitioned risk assessment (Case Mixed-Zone division: T50P50Z) demonstrated enhanced fire mitigation, closely matching the performance

of the fully protected ceiling (Case FP). This strategy not only effectively delays ceiling ignition and reduces the rate of fire spread but also preserves the structural benefits of increased timber content without exacerbating fire severity. However, the present study does not explicitly analyze local behaviour at interfaces between zones of differing strip width and possible flame spread across these transition areas remains a limitation. As a potential mitigation, transition buffer bands (wider, non-combustible laps), together with strict requirements for encapsulation continuity and sealed joints at interfaces, are recommended. Future work will quantify the sensitivity of interface flame spread to width gradients.

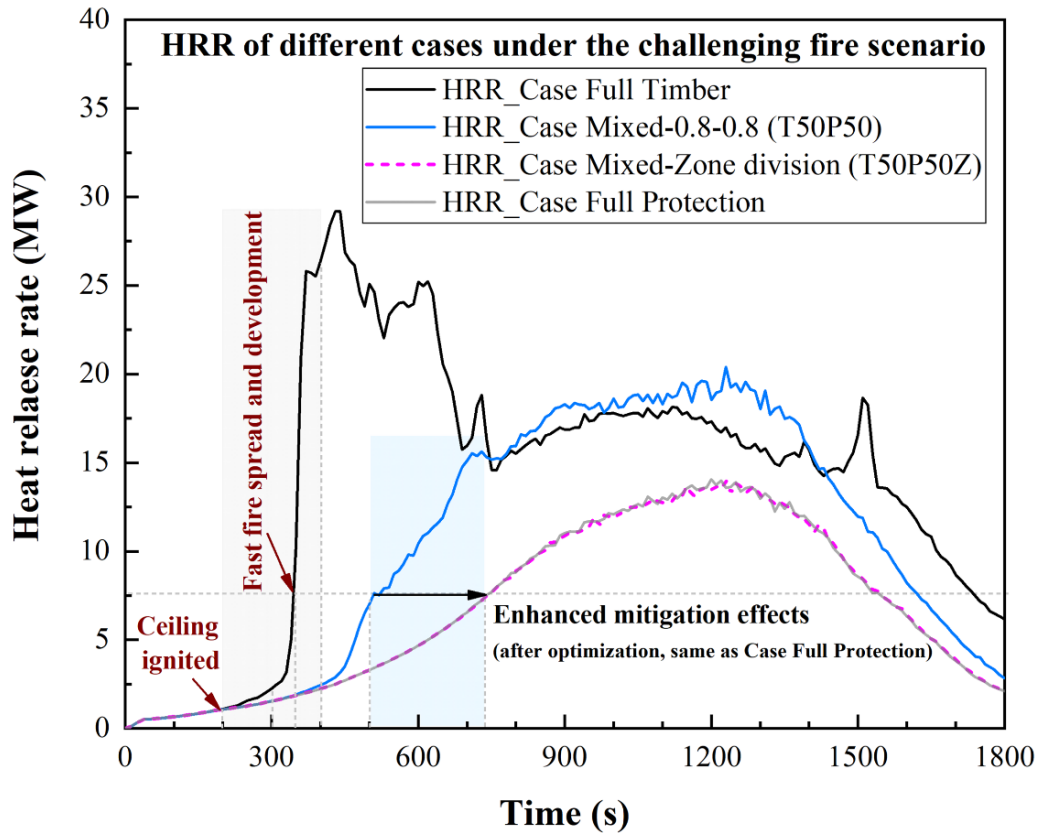


Fig. 5.21. Evolution of HRR in compartments with different ceiling configurations under the challenging fire scenario.

Although the optimized mixed ceiling was not able to keep the fire localized for 30 minutes in the above mentioned challenging fire scenario, as it had been in the previous, milder fire case, it was still effective in controlling the development of the fire in the compartment, inhibiting the rapid initial spread. Overall, the partitioned protection concept, leveraging flexible strip width combinations in timber-insulation mixed ceilings, offers an effective and adaptable solution for improving fire safety and structural performance in large open-plan timber compartments. These findings provide essential guidance for performance-based fire safety design, highlighting the potential for tailored fire protection strategies that balance fire risk management with structural integrity considerations.

To ensure the appropriate application of the timber-insulation mixed ceiling strategy, parametric analyses should be carried out on the design of relevant strip combinations for real building fire scenarios. Ideally, a reasonable combination of strip widths could be designed based on the use of the building and the initial division of the building area, e.g. wider insulation strips in localized areas with a dense distribution of combustibles. These analyses will include transition-zone detailing so that interface performance under fire can be assessed with refined simulations and targeted experiments, thereby improving system reliability. In addition, the proposed strategy, together with an active opening strategy [119, 153] based on a temperature-smoke detection system for compartment openings at a suitable initial opening height, can provide a reference for fire safety design in real building fire scenarios by providing further effective smoke evacuation. Further development and research work have been scheduled to achieve more suitable deployment strategies and effectiveness in various compartment configurations. To this end, a number of numerical studies and large-scale experimental tests will be carried out as future work.

5.5. Conclusion

This study presents a comprehensive investigation into the application of the timber-insulation mixed ceiling strategy within large open-plan compartments, specifically focusing on the challenges posed by exposed timber surfaces in fire safety scenarios. Based on a validated CFD fire model developed from the Malveira fire test, the effectiveness and robustness of the proposed timber-insulation mixed slab design were evaluated under various challenging and extreme fire scenarios involving non-uniform fuel load distributions and differing ventilation conditions. Key conclusions drawn from the research are summarized as follows:

1. Through systematic CFD simulations, the study demonstrates that traditional assumptions of uniformly distributed fuel loads underestimate fire risk in large open compartments. Non-uniform and discontinuous fuel arrangements, reflective of challenging building scenarios, exhibit accelerated local fire growth and higher heat release rates. Thus, performance-based fire safety design practices must incorporate non-uniform fuel load considerations to ensure accurate fire risk assessments.
2. Investigations into different beam configurations reveal that beam geometry influences fire dynamics. Deep beams (with a higher vertical section) tend to obstruct smoke movement, resulting in localized heat accumulation, rapid fall of the smoke layer, and earlier full development of fire conditions. Although deep beams typically offer superior structural performance, flat beams provide structural benefits relative to a flat ceiling without substantially exacerbating fire spread. This presents an optimal balance between structural and fire safety considerations.

3. Ventilation conditions, specifically the height of compartment openings, play a critical role in fire behavior within compartments featuring mixed ceiling designs. Lower opening heights facilitate smoke accumulation, intensifying localized thermal feedback and accelerating fire development. Higher openings enhance smoke evacuation efficiency, slowing fire progression and reducing overall compartment fire intensity.
4. The inherent flexibility in the design and arrangement of mixed ceilings allows for optimization of the arrangement according to the fire level of the different zones, further enhancing fire performance in extreme fire situations.

Overall, the proposed timber-insulation mixed-ceiling strategy provides a novel reference solution for the fire safety design of timber structures. When integrated with the code-required mechanical or natural ventilation system already common in modern compartments, the mixed ceiling can further limit fire spread without sacrificing the open character of the building. Future work should include detailed parametric studies and large-scale experimental validations to refine the strategy's practical application, especially under diverse and realistic fire scenarios.

Chapter 6: Numerical simulation of timber composite slabs in fires using OpenSees for fire

Summary

Chapter 6 integrates the modelling approaches from the previous chapters to simulate the fire performance of timber composite slabs. It presents a comprehensive numerical model on the OpenSees for fire platform that employs an orthotropic plastic-damage formulation, capturing the anisotropic degradation of timber properties under elevated temperatures. By unifying the advanced heat transfer model from Chapter 2 with the structural analysis techniques from Chapter 3, the framework dynamically updates material stiffness based on temperature, enabling realistic predictions of the slab's structural response and failure progression during fire exposure. Validated against full-scale experimental data, the model accurately captures deflection histories and failure modes in CLT slabs. Furthermore, Chapter 6 applies this model to timber slabs featuring the timber-insulation mixed ceiling (developed in Chapters 4 and 5) and, by comparing it with full timber composite (FTC) slabs under different fires, highlights the greater fire resilience of the proposed mixed ceiling strategy, which delays heat penetration by mitigating fire development and thus reduces the loss of stiffness and maintaining higher residual load carrying capacity. The above description has resulted in an integrated performance-based design approach that combines detailed CFD fire modelling inputs with thermomechanical analysis in OpenSees for fire. This integrated simulation capability, by combining thermal analysis, structural modelling, and innovative slab design, enables engineers to assess the thermomechanical performance of complex timber slab systems under realistic fire scenarios and supports the development of fire-resilient slab systems in future timber buildings.

This chapter is based on “[C. Chen, J. Zhao, J. Qiu, A. Usmani, L. Jiang*](#) (2025). Numerical simulation of timber composite slabs in fires using OpenSees for fire. **Engineering Structures** (Pending to submission).”

6.1. Introduction

Driven by low-carbon initiatives, engineered timber products like cross-laminated timber (CLT) and glued-laminated timber (Glulam) are increasingly used in construction for their sustainability benefits. Modern architectural designs often feature exposed timber surfaces for aesthetic appeal, avoiding traditional fire-resistant coverings. However, the combustibility of timber presents a critical challenge to its wider application.

In structural terms, two-way spanning timber slabs play a key role in modern large open-plan timber compartments, but the corresponding behavior under fire is not yet fully clarified. Most research to date on timber in fire has focused on one-way load-bearing slab elements [154-156]. Two-way slabs differ from one-way components in that load is carried in both principal directions, meaning the weaker, perpendicular-to-grain layers must resist tension and shear. This anisotropy makes two-way slabs more susceptible to certain failure modes under load and heat. For example, small-scale tests on two-way CLT slabs at ambient temperature found failure by transverse tensile rupture at the slab bottom [157], owing to the low perpendicular-to-grain tensile strength. In full-scale fire tests on two-way CLT slabs, failure (excessive deflection) was observed at roughly 50 minutes of fire exposure [158]. Moreover, when a CLT slab forms part of a large compartment ceiling, the involvement of the timber in the fire can be an additional fuel source and exacerbate flame spread during the heating phase [44, 45, 68] and even extend burning during the cooling phase [19]. These observations highlight that two-way timber slabs in large compartments pose a different structural fire response risk that differs from one-way members. There is a clear need for further investigation of two-way timber slab performance in fire, including both experimental studies and advanced simulations.

Full-scale fire testing of timber floor systems is expensive and limited in scope, so numerical modelling has become a critical tool for evaluating timber structures in fire. Design codes such as Eurocode 5 (EC5) [94] provide simplified calculation methods (e.g. the effective cross-section method, which assumes complete strength loss in charred layers) for timber components in fire. Following this code and partial fire-resistant tests on different timber elements (e.g., CLT slabs [34, 82], glulam beams [84], solid timber beams [83], and CLT walls [81]), structural timber has been used in some implemented timber building projects. However, due to the complexity of the combustion behavior of timber, multi-stage physical transformations and chemical reactions are involved [24, 25]. Firstly, for heat transfer analysis of exposed timber members, neither the standard code (EC5) [94] nor the evolutionary models (EC5-type models) [23, 24] calculations consider the additional heat generated by the burning timber, which can lead to inaccuracies in the prediction of the cross-sectional heat distribution of timber members. Second, for structural response analysis, since timber is orthotropic, it exhibits different mechanical properties in the parallel and perpendicular to the grain (and shear) directions [54]. High-temperature-induced charring and strength

degradation further complicate the mechanical behavior of timber under fire [[19, 159]. Nonetheless, some researchers have made important advances in this area. Dârmon and Lalu [84] developed a thermo-mechanical model for timber beams under standard fires using SAFIR [87]. Fragiaco et al. [34] and Menis [88] employed a concrete damage-plasticity approach in ABAQUS [160] to model CLT panels, capturing the orthotropic behavior at ambient conditions and then degrading properties in fire. More recently, Chen et al. [50] extended the OpenSees for fire platform [48, 49, 107] to include layer-based heat transfer and thermo-mechanical material models for timber, enabling simulation of timber members under non-standard fire exposures. However, the aforementioned models either do not consider the extra fire load from burning timber or are limited to one-way structural components. It is thus important to advance numerical tools to evaluate the fire performance of two-way timber slabs under realistic conditions.

This study introduces and validates an advanced modelling approach for two-way timber slabs under fire within the OpenSees framework. The proposed model incorporates a layer-based heat transfer model and an orthotropic damage-plasticity material model to capture the mechanical response parallel and perpendicular to the grain, including temperature-driven degradation. Thermomechanical shell elements (*ShellNLDKGQThermal*) with *LayerShellSectionThermal* model timber cross-sections, while a wrapper section (*PlateRebarThermal*) captures weak-axis effects in two-way slabs for efficient load-bearing simulation. The model is validated against a full-scale two-way CLT slab fire test from the literature and then used to explore a novel composite slab design that alternates timber and insulation on the underside to mitigate fire spread. The work presented in this study, along with future developments, will remain open-source and freely accessible via the website: opensesforfire.github.io, to support performance-based fire design of modern timber floor systems.

6.2. Simulation platform of OpenSees for fire

OpenSees was originally developed at UC Berkeley as an Open System for Earthquake Engineering Simulation [47]. Using its modular, object-oriented architecture, a fire simulation extension (OpenSees for fire) has been developed over the years [48, 49]. This extension introduces modules for defining fire thermal actions, conducting heat transfer (HT) analysis on structural members, and performing thermomechanical structural analysis under fire. The software framework of OpenSees for fire [48-50] comprises a thermal domain (with HT elements, materials, and boundary conditions to simulate heat transfer) and a structural domain (with temperature-dependent material models, sections, and elements, as well as ThermalAction objects to apply temperature histories). Analyses can be scripted in Tcl or Python, which the OpenSees interpreter executes to carry out the coupled computations.

6.2.1. Previous work on modelling of slabs in fire using OpenSees

Modelling floor slabs is critical for evaluating structural response to fire, and several extensions to

OpenSees have been developed to simulate slab behavior at elevated temperatures. Early attempts employed MITC4 shell element [161] with a Drucker-Prager material to model concrete slabs. While this was adequate at ambient temperature, it lacked the nonlinear formulations needed to capture large deflections under fire loading [161]. Lu et al. [162] later developed a geometrically nonlinear shell element (DKGQ) for seismic collapse simulation, which was subsequently enhanced to include thermal effects. This enhancement enabled a layered representation of slabs in fire, where each layer through the thickness could be assigned temperature-dependent material properties. Building on that, Jiang et al. [91] introduced a nonlinear layered shell element capable of capturing large deflections under fire by using multiple material layers through the slab thickness. The resulting *LayeredShellThermal* V1.0 section [163] only requires the user to specify the material model and thickness for each layer, simplifying the modelling of composite slabs. Additionally, a plane-stress concrete damage-plasticity model at elevated temperatures was implemented in OpenSees to more accurately simulate concrete slab cracking under fire conditions.

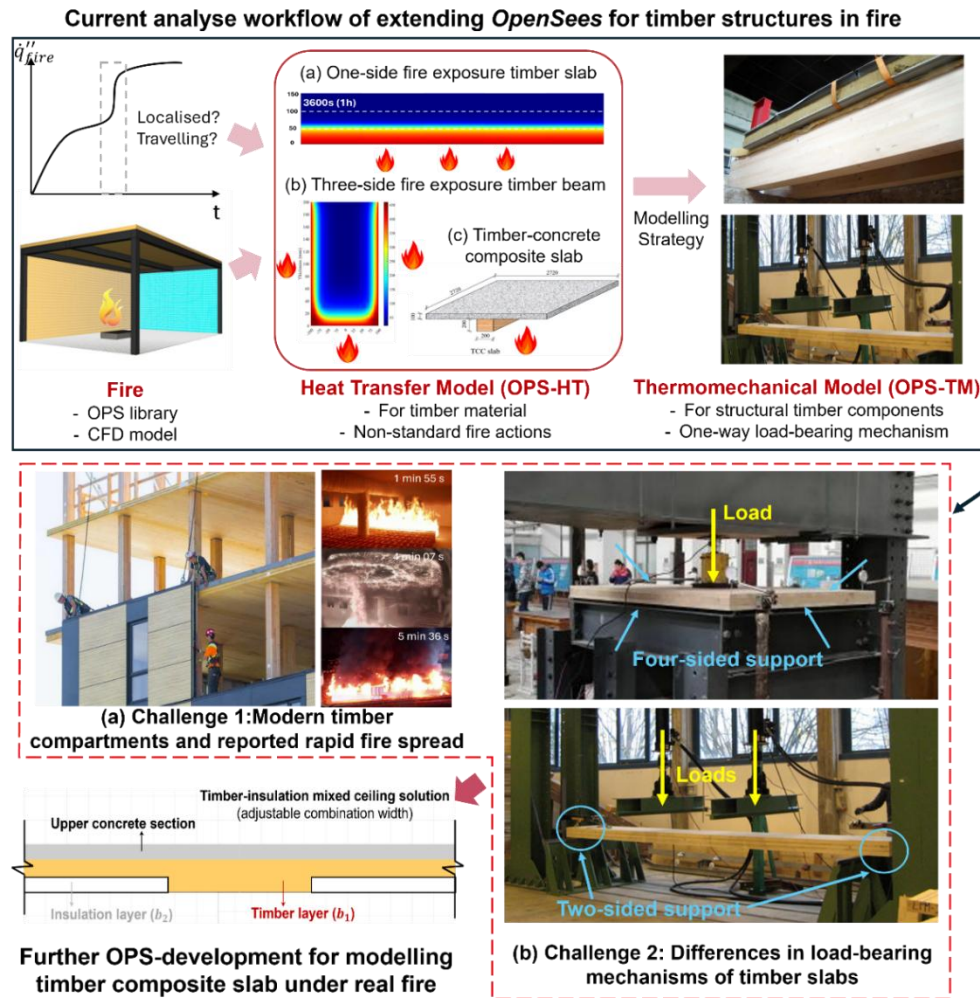


Fig. 6.1. Preliminary extension of OpenSees for fire for modelling timber structures in fire [50] and further research needs based on modern timber buildings.

Fig. 6.1 illustrates the preliminary extension of OpenSees for fire to timber structures and emerging research needs. Building on the above foundation, Chen et al. [50, 92] extended OpenSees for fire to model timber members. The relevant work included developing a layer-based heat transfer model (OPS-HT) for timber material and thermo-mechanical material models (OPS-TM) for timber beams, columns, and slabs with temperature-dependent properties. These advances made it possible to simulate timber elements under natural fire scenarios within OpenSees for fire. However, modelling two-way timber slab systems in realistic compartment fires remains challenging. Recent large-scale fire experiments have shown that an exposed CLT ceiling (34 m by 10 m) can be engulfed by fire in just a few minutes and that conventional continuous block encapsulation cannot mitigate the rapid spread of fire. These phenomena highlight the need for improved modelling approaches and innovative structural design strategies to mitigate fire spread. Addressing these challenges is the focus of the present work. the following sections introduce and validate a specialized material model and modelling methodology for two-way load-bearing timber slabs against experimental data and apply them to investigate a composite slab solution for enhanced fire performance.

6.3. Development of the material model for two-way load-bearing mechanism timber slabs

Two-way spanning CLT slabs differ from one-way members in that they engage multiple layers and directions in resisting loads, leading to complex failure modes under fire. Key challenges in modelling their behavior include: (1) inter-layer shear interaction (rolling shear) between the perpendicular layers, (2) different failure characteristics in tension and shear (which tend to be brittle) versus compression (which can have some plastic reserve), and (3) strongly orthotropic elastic and strength properties along the grain (longitudinal, L) and across the grain (transverse, T). Many conventional damage models assume isotropic stiffness degradation, which cannot capture the progressive, direction-specific failure of timber fibers in a slab composed of cross-laminated layers. To address these issues, a specialized orthotropic damage-plasticity material model was developed to represent timber. This model assigns distinct strength and damage parameters to the principal material directions (parallel-to-grain L and perpendicular-to-grain T), allowing each to degrade independently under fire conditions as the material chars and loses strength.

6.3.1. Experimental evidence and orthotropic behavior under fire

Timber exhibits orthotropic behaviour due to its fibrous cellular structure, with markedly different properties along the longitudinal, radial, and tangential directions [164]. Under elevated temperatures, thermal degradation of hemicellulose and lignin weakens the transverse bonding between fibres more severely than the longitudinal stiffness, leading to a temperature-dependent but persistent anisotropy. Dynamic mechanical analysis by Adibaskoro et al. [165] on spruce confirmed that although the elastic moduli in all directions decrease with temperature up to 300 °C, the ratio between parallel-to-grain and perpendicular-to-grain stiffness remains high, evidencing sustained orthotropy during heating.

At the structural scale, Wiesner et al. [166] experimentally investigated the rolling-shear strength of CLT between 20 °C and 200 °C and found a 50 % and 75 % reduction at 100 °C and 200 °C, respectively. Nevertheless, bending failure in the strong (longitudinal) layers still dominated, indicating that while orthotropic strength contrast diminishes, it remains significant even near charring temperatures. Similar behaviour has been reported for glulam and LVL members, where along-grain strength decays more gradually than transverse shear and compression, consistent with anisotropic degradation of wood polymers [22]. These observations collectively justify implementing an orthotropic plastic-damage model in OpenSees for fire, allowing distinct temperature-dependent reduction factors in each principal direction. This formulation reproduces differential stiffness loss and internal stress redistribution observed in full-scale CLT fire tests, ensuring that both bending governed, and shear governed responses are captured realistically.

6.3.2. Ambient temperature constitutive behavior

As shown in Fig. 6.2a, the ambient-temperature constitutive law for timber in this model is based on a nonlinear stress–strain relationship proposed by Glos [97] and later linearized by Hartnack [102]. In compression, the stress–strain curve exhibits an initial elastic portion followed by a yield plateau up to the ultimate compressive stress. Key parameters (such as the strain ε_0 at peak compressive stress $f_{c,0}$ and the elastic modulus E) define this curve, and they are calibrated to typical timber behavior in compression. In tension, timber failure is brittle with little plastic deformation. To reflect this, the model uses a sudden post-peak stress drop: once the tensile strength is reached, the tensile stress is reduced almost to zero over a very small strain interval (~ 0.001 beyond the peak). This simulates the rapid fracture of timber in tension while maintaining numerical stability [50] in the analysis.

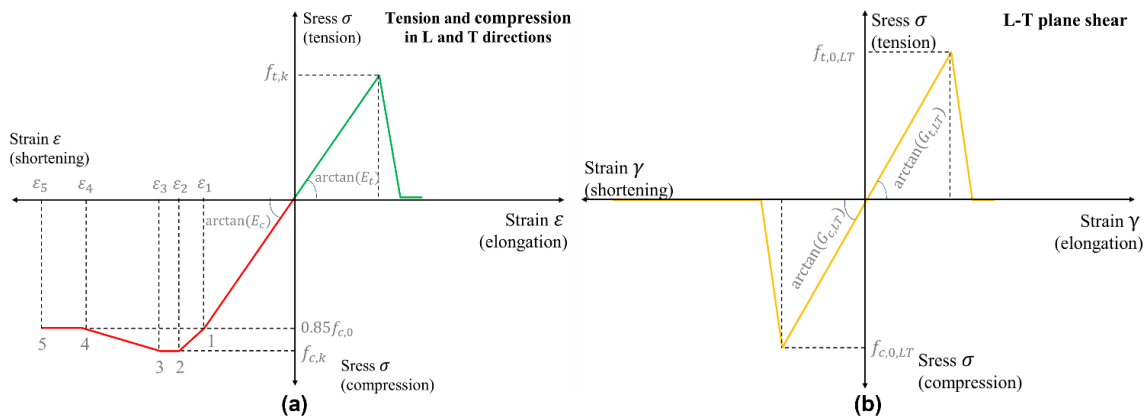


Fig. 6.2. The relationships between stress and strain of timber.

In a similar manner, the in-plane (rolling) shear failure is treated as a brittle mode. The shear stress–strain response uses the same approach as the tensile model [167], with a sharp drop in shear resistance after the shear strength is reached. The material is defined to respond identically in positive and negative

shear directions to handle any load reversals symmetrically. By adopting independent brittle failure criteria for tension and shear, and a nonlinear plastic response for compression, the model can capture the different failure mechanisms of timber in each principal direction. The corresponding constitutive model consists of the strain γ_0 corresponding to the ultimate shear stress (f_{LT}) and the shear modulus G_{LT} , as shown in Fig. 6.2b.

6.3.3. Damage evolution model based on stiffness updating for timber

Damage evolution is tracked with separate internal damage variables for the L and T directions. A strain energy-based criterion is used to drive damage: the strain energy density as shown in Eq. 6.1 [168], in each direction is tracked and compared to the fracture energy g_f for that direction. If the energy exceeds g_f , the corresponding damage variable increases (following a predefined evolution law) to represent crack formation and growth. If it is below the threshold, damage accumulates more gradually. At each analysis step, the stiffness in each direction is scaled by a factor $(1 - D)$ based on the current damage variable in that direction. For example, the longitudinal Young's modulus E_L is multiplied by $(1 - D_L)$ and the transverse modulus E_T by $(1 - D_T)$, according to the respective damage states (Eq. 6.2 and Eq. 6.3). As damage D_L or D_T grows from 0 (intact) toward 1 (fully failed), the corresponding directional stiffness and strength degrade proportionally. This formulation enables progressive, direction-specific stiffness loss (rather than an abrupt or isotropic loss), which is important for capturing the gradual failure of layered timber slabs under increasing fire exposure.

$$W = \frac{1}{2} \times E \times \varepsilon^2 \quad (6.1)$$

$$D_{L, \text{ current}} = (1 - D_L) \times E_L \quad (6.2)$$

$$D_{T, \text{ current}} = (1 - D_T) \times E_T \quad (6.3)$$

6.3.4. Temperature-dependent property update

High temperatures further weaken timber, and the model updates the material parameters in real time as the temperature in each element rises. The temperature-dependent reduction factors are based on EC5 [94] recommendations for timber properties in fire. At ambient temperature (20 °C), the timber retains its full strength and stiffness. Above 20 °C, the elastic modulus and the tensile/compressive strengths decrease in a segmented linear pattern over specified temperature ranges (following the EC5 degradation curves). By around 300 °C, the residual strength and stiffness are taken to be effectively zero, representing the charred state of the material. Shear strength is degraded in a similar manner over the temperature range. Fig. 6.3 illustrates the assumed reduction factors for timber strength and stiffness. These temperature-dependent reductions are incorporated directly into the constitutive model via a parameter-update function at each time step.

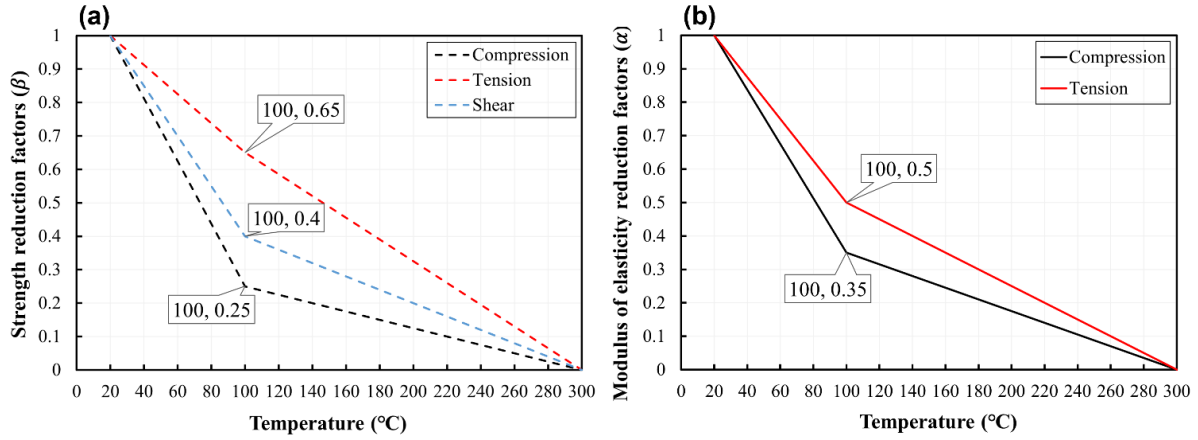


Fig. 6.3. Reduction factors for timber material properties at elevated temperature: (a) Compressive, tensile and shear strength; (b) Elastic modulus for compression and tension.

6.3.5. Implementing thermomechanical analysis of two-way flat timber slab in OpenSees

Fig. 6.4 presents a flowchart of the modelling and analysis procedure for a two-way timber slab under fire in OpenSees. The implementation primarily utilised the existing OpenSees framework for layered shell elements (originally developed for concrete slabs) with the new timber material model described above. The overall simulation process can be summarized in four main steps: (1) defining the nodes of the shell elements; (2) defining the layered shell sections of the CLT slab; (3) defining the shell elements; and (4) applying the thermal action.

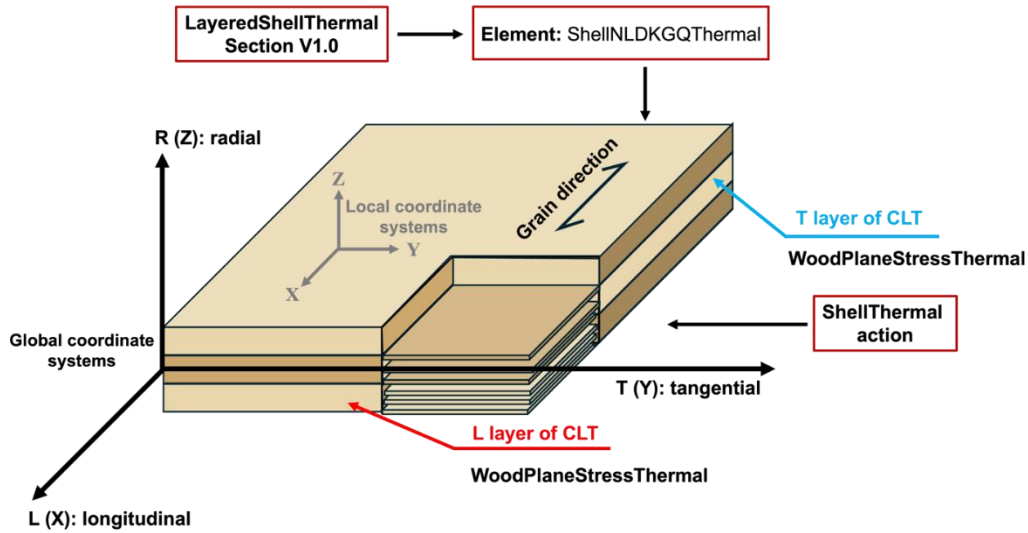


Fig. 6.4. Thermal-mechanical analysis of two-way flat timber slab in OpenSees under global and local coordinate systems.

Specifically, to accurately simulate the orthotropic mechanical behaviour of the CLT slab, the material's stiffness matrix is formulated in a local coordinate system aligned with the timber grains. The grain direction of the timber aligned with the global X-axis is treated as the L-direction, and the

perpendicular grain direction (global Y-axis) as the T-direction in the model. Two plane orthotropic material instances are defined: one for an L-layer (timber layer with grain parallel to X) and one for a T-layer (grain perpendicular to X). These two material models have the same set of properties but with the longitudinal and transverse values swapped. For example, the L-layer material uses the strong-axis modulus and strength (parallel-to-grain, $E_{pos,L0}$, $E_{neg,L0}$, $f_{t,L0}$, and $f_{c,L0}$) in the global X direction and the weaker perpendicular-to-grain properties ($E_{pos,T0}$, $E_{neg,T0}$, $f_{t,T0}$, and $f_{c,T0}$) in the Y direction. Conversely, the T-layer material is defined with $E_{pos,T0}$, $E_{neg,T0}$, $f_{t,T0}$, and $f_{c,T0}$ along global X and $E_{pos,L0}$, $E_{neg,L0}$, $f_{t,L0}$, and $f_{c,L0}$ along Y. In this way, each material model still accounts for the orthotropic behaviour in both its parallel and perpendicular axes. These two material models are then used to construct the layered shell section for the slab. Using an OpenSees wrapper (*PlateFromPlaneStressThermal*), the plane-stress materials are assembled into a *LayeredShellThermal* section, arranging L-layer and T-layer materials in the correct sequence to represent the CLT layup. For instance, a 5-layer slab with layup L–T–L–T–L and 21 mm per layer is modelled by alternating the two material types accordingly. Fig. 6.5 shows an example Tcl script defining the materials and section for such a CLT slab. In the current model, perfect bonding is assumed between all layers (no delamination or slip at interfaces). This assumption is consistent with the typical behaviour of fully bonded CLT and maintains a simpler, unified model for the composite slab. Although the L- and T- layers are defined with separate material models, the perpendicular-to-grain stiffness of each layer is inherently included via the orthotropic properties (e.g. each L-layer material still has a finite transverse stiffness corresponding to the T-direction properties, and vice versa). This ensures that each layer can carry load in both global directions according to its orientation.

```
# Create material models
# nDMaterial WoodPlaneStressThermal $matTag $E_pos,L0 $E_neg,L0 $f_t,L0 $f_c,L0 $E_pos,T0 $E_neg,T0 $f_t,T0 $f_c,T0 $G_LT0 $f_LT0 $g_fL $g_fT
nDMaterial WoodPlaneStressThermal 4 $E_pos,L0 $E_neg,L0 $f_t,L0 $f_c,L0 $E_pos,T0 $E_neg,T0 $f_t,T0 $f_c,T0 $G_LT0 $f_LT0 $g_fL $g_fT; # For L layer
nDMaterial WoodPlaneStressThermal 5 $E_pos,T0 $E_neg,T0 $f_t,T0 $f_c,T0 $E_pos,L0 $E_neg,L0 $f_t,L0 $f_c,L0 $G_LT0 $f_LT0 $g_fL $g_fT; # For T layer
# nDMaterial PlateFromPlaneStressThermal matTag nDMatTag forStability
nDMaterial PlateFromPlaneStressThermal 6 4 1e9;
nDMaterial PlateFromPlaneStressThermal 7 5 1e9;
# Create sections
# set $secName $secTag
set flatsec 1
#section LayeredShellThermal secTag numoflayers mat1Tag mat1Thickness mat2Tag mat2Thickness ... matnTag matnThickness
section LayeredShellThermal $flatsec 5 6 0.021 7 0.021 6 0.021 7 0.021 6 0.021;
```

Fig. 6.5. Examples of material definitions of CLT slab in Tcl scripts for OpenSees for fire.

6.3.6. Modelling procedure in OpenSees for fire for two-way timber slabs in fire

Fig. 6.6 provides an overview of the modelling workflow. Essentially, the orthotropic elastic and strength parameters in the material model are initialized for the longitudinal, transverse, and shear directions,

then updated at each time step based on the local temperature. The damage evolution model reduces the stiffness in each direction as failure progresses. Through this approach, the simulation captures both the gradual stiffness decay of the timber slab and the ultimate load capacity reduction as failure occurs during fire exposure.

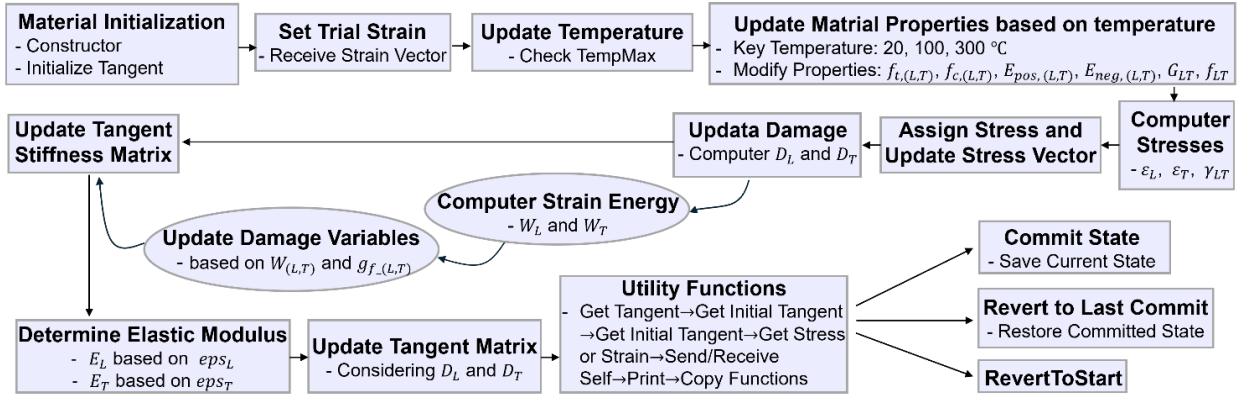


Fig. 6.6. Workflow of modelling two-way load bearing timber slabs to fire in OpenSees framework.

6.4. Validation: Fire resistance modelling of a two-way CLT slab

As a first validation, the model was applied to a simply-supported two-way CLT slab that was tested in a fire by Xing et al. [158]. The test specimen was a CLT slab measuring $3.8 \text{ m} \times 2.2 \text{ m}$ in plan and 105 mm thick, consisting of five layers of 21 mm thickness (layup L–T–L–T–L). The timber had an average density of 430 kg/m^3 and 12 % moisture content. The slab was supported along all four edges with a clear span of approximately $3.6 \text{ m} \times 2.0 \text{ m}$ between supports. Prior to the fire, a service load of 150 kN was applied (distributed at 12 points on the slab) to represent floor loading as shown in Fig. 6.7, and this load was maintained throughout the fire. The fire exposure followed a parametric fire curve in a furnace, intended to simulate a compartment fire. Due to the limited availability of two-way timber slab fire tests, this single test was used as the basis for validating the model.

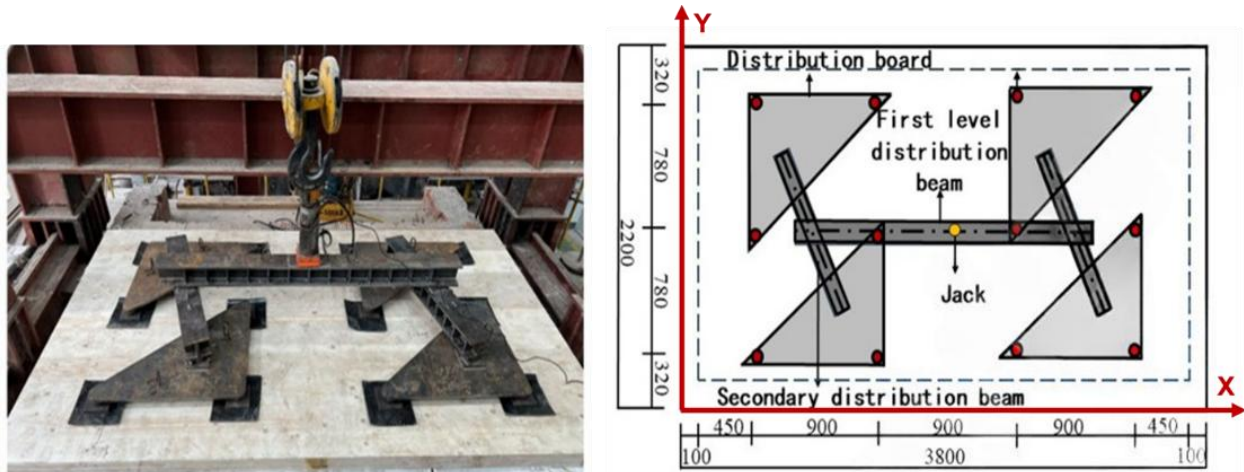


Fig. 6.7. Schematic diagram of CLT two-way slab fire resistance test loading device [158].

The material properties for the CLT slab in the simulation were not fully specified by the test report, so they were assumed based on a typical mid-grade softwood (approximately corresponding to the C24/C27 classes of EN 338 [169]) was adopted based on the reported average density ($\sim 430 \text{ kg/m}^3$). The ultimate tensile strength of the timber fiber in the L direction is 15.0 MPa ($f_{t,L0}$), the ultimate compressive strength is 21.5 MPa ($f_{c,L0}$), and the modulus of elasticity is taken as 11,250 MPa ($E_{\text{pos},L0}$ and $E_{\text{neg},L0}$). In the T direction, the ultimate tensile strength is 0.4 MPa ($f_{t,T0}$), and the ultimate compressive strength is 2.55 MPa ($f_{c,T0}$), which corresponds to a modulus of elasticity of 375 MPa ($E_{\text{pos},T0}$ and $E_{\text{neg},T0}$). In the LT direction, the ultimate shear strength is 4.0 MPa (f_{LT0}), and the corresponding modulus of elasticity is 705 MPa (G_{LT0}). In addition, the fracture energies in the L and T directions are 10 MPa ($g_{f,L}$) and 2.9 MPa ($g_{f,T}$), respectively.

6.4.1. Modelling heat transfer of the CLT slab

The compartment fire in the test was described by a parametric fire curve (following Xing et al. [158, 170]) representing a design office fire. The compartment dimensions were 3.6 m (length) $\times$ 2.0 m (width) $\times$ 3.0 m (height) with a window opening of 1.0 m $\times$ 2.0 m. The fire load density was 420 MJ/m², typical for an office occupancy [94]. In the test, the slab was subjected to heating from 24 minutes (when the furnace burners ignited) until 72.6 minutes, followed by a cooling (decay) phase. For the simulation, a 2D heat transfer model of the CLT cross-section was created in OpenSees. The cross-section (105 mm thick) was discretized with 1 mm thick HT elements through the depth. Boundary conditions were applied according to Eurocode 1 (EC 1) [94]: a convective heat transfer coefficient of 25 W/m²K on the fire-exposed surfaces and 4 W/m²K on the unexposed face, and an emissivity of 0.8 for the timber surface to consider radiation. . For the heat transfer material model, the parameters of the reported material were used.

Fig. 6.8 compares the predicted and measured temperatures at various depths in the slab cross-section. In the test, thermocouple bundles were embedded at multiple depths and the shaded bands in comparison represent the range (max–min) of readings from thermocouples at the same depth, indicating some variability in the measurements. The temperatures at 8, 16, 24 mm from the exposed face and at 32, 40, 48 mm are compared in Fig. 6.8a and 6.8b. Overall, the OpenSees heat transfer model shows good agreement with the test data across all measured depths. The main differences appear in the 95-125 °C range, which corresponds to the water evaporation plateau phase of the timber: the simulated temperature rise at these depths is faster compared to the test. On the one hand, this may be due to the higher moisture content of the test samples than the reported values, and on the other hand, it may be that some of the heat was carried away by the evaporation of the timber water during the experiments, which resulted in not capturing this phase perfectly. Even in the test data, there was considerable dispersion, e.g. during the evaporation phase, the thermocouple readings varied by up to almost 80 °C at a depth of 8 mm.

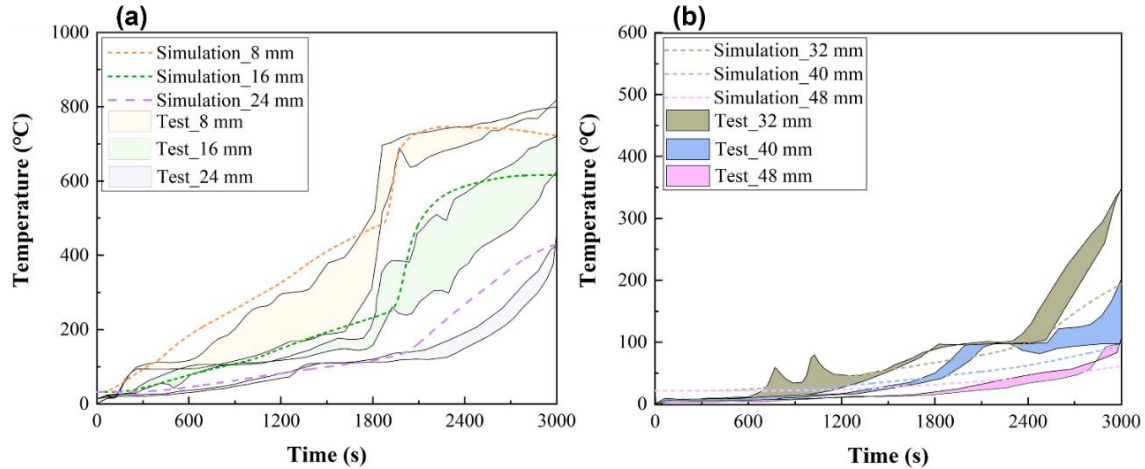


Fig. 6.8. Thermal response of test specimen exposed to parametric fire.

In the later cooling phase, some near-surface thermocouples (at 8 mm and 16 mm) in the experiment registered temperatures that rose back close to the hot gas temperature, suggesting that portions of the char layer cracked or fell off, briefly exposing those sensors to the furnace atmosphere. The developed OpenSees heat transfer model (OPS-HT model), which does not explicitly include char fall-off, so it did not reproduce the abrupt temperature peaks. Instead, the predicted temperatures show a smoother cooling process. Despite these differences, the thermal model is deemed sufficiently accurate for structural analysis under fire. Aside from these localized effects, the thermal model is considered sufficiently accurate for the initial purposes, it reproduces the temperature–time profiles through the timber with only minor deviations. These temperature profiles will be used as input for the structural analysis. To that end, a set of nine representative through-thickness temperature points was extracted from the model (corresponding to the integration points of the structural layer model). To ensure conservative thermal loading, an alternative temperature profile using the average of the hotter thermocouple readings in the test for the near-surface layers (before 48 mm) were also prepared, combined with the fitted values for the inner layers (after 48 mm) based on similar trends to form the complete temperature data. This temperature profile accounts for the possibility of slightly faster heating near the surface than the model predicted (representing char fall-off), while preserving the overall accuracy of the deeper temperatures.

6.4.2. Modelling thermomechanical behavior of two-way CLT slab

The structural model of the test slab used the net span dimensions (approximately $3.6 \text{ m} \times 2.04 \text{ m}$ between supports) with simply-supported boundary conditions on all edges. The shell mesh consisted of 40 elements along the length and 34 along the width of the slab, giving a roughly $90 \text{ mm} \times 60 \text{ mm}$ element size. The total applied load of 150 kN (distributed at 12 points in the experiment) was converted to an equivalent uniform pressure of about 104.5 kN/m^2 on the slab surface. This load was applied as a static pre-load in the model before the fire temperatures were introduced. The slab was modelled with shell elements

(*ShellNLDKGQThermal*), which are desirable to describe the behaviour of CLT slabs of two-way mechanism. For the shell element model, the section defined using *LayerShellSectionThermal* comprises multiple layers of plate fibre type material (15 layers used in this model). Each layer was assigned the *WoodPlaneStressThermal* material corresponding to either an L or T orientation as appropriate for the CLT layup

For the time-dependent analysis, the fire was applied following the same timeline as the test. The mechanical load was applied to 150 kN by 24 min (pre-fire) and then held constant. From 24 min onward, the 9-point through-thickness temperature history (determined from the heat transfer analysis, as discussed above) was applied to the shell section using *ShellThermalAction*. The temperature at each of the 9 integration points in the section was updated at each time step, with linear interpolation between those points to define a continuous temperature profile through the depth. The analysis was carried out until 72.6 min (when the fire exposure ended, and structural failure was approaching in the test) and then terminated. Throughout the simulation, the mid-span deflection of the slab was recorded for comparison with the experimental deflection–time curve. To examine the influence of the thermal input on results, two cases were executed: (1) using the “Exp. Calibrated” temperature profile which utilized test-measured temperatures for the near-surface points and interpolated/fitted values for the interior points (red dashed curve), and (2) using the purely “HT-Model Predicted” temperature profile from the developed heat transfer simulation [92] with no calibration to test data (blue dotted curve). These two cases bound the possible thermal input uncertainties, with the first case likely representing a slightly more severe near-surface heating (since it indirectly accounts for any char fall-off effects observed in the test). Fig. 6.9 qualitatively illustrates the observed failure mode of the slab in the fire test.



Fig. 6.9. Reported phenomenon of CLT two-way slab fire resistance test by Xing et al. [158].

Fig. 6.10 compares the central deflection of the slab from the experiment and the OpenSees simulations. During the initial loading phase at ambient temperature (0–1440 s, i.e. up to 24 min), the OpenSees model’s deflection closely matches the measured deflection, indicating that the elastic stiffness of the slab and support conditions were well represented. Once the fire heating begins (after 1440 s), the slab’s deflection in the test accelerates as the bottom layers char and lose stiffness.

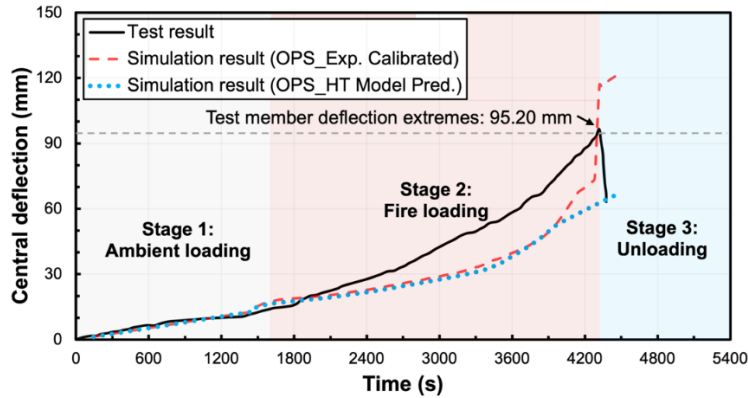


Fig. 6.10. Illustration of experimental and numerical displacement of F2 CLT slab test specimen [158] at ambient temperature and fire load.

Both simulation cases reproduce the general trend of increasing deflection, but they under-predict the rate of deflection growth during the fire. The Exp. Calibrated case (red dashed curve in Fig. 6.10) comes closer to the test, capturing the timing of the sharp deflection jump that signifies failure (around 4210–4340 s in both simulation and test). However, the peak deflection in the simulation is slightly lower than the test measurement at failure. This minor underestimation is likely because using averaged thermocouple temperatures in the model under-represents the hottest spots at the slab mid-span effectively, the thermal gradient driving the deflection is a bit less severe in the model than in the test, resulting in a smaller deflection. By contrast, the HT-Model Predicted case (blue dotted curve in Fig. 6.10) shows a more gradual increase in deflection and does not exhibit the sudden drop-in stiffness that corresponds to failure in the test. This case predicts a slightly longer time to failure and a lower maximum deflection. The difference between the two simulation cases can be traced to the thermal input: the purely predicted temperature profile did not account for potential char fall-off or other mechanisms that might have allowed deeper heating in the actual slab. The heat transfer model did not consider the mechanical cracking of char, so it underestimates internal temperatures in the later stages of burning (as seen in Fig. 6.8). Consequently, the structural response in the OPS_HT Model Pred. case is conservative (less damage and deflection than reality). Another factor is the uncertainty in timber material properties. The strength and stiffness of the actual CLT may have been slightly lower than the generic values we assumed, which would cause the real slab to fail a bit sooner. Overall, considering these uncertainties, the OPS_Exp. Calibrated case provides a good match to the test, capturing the failure time and mode within a reasonable tolerance.

In summary, the validation demonstrates that the OpenSees model can realistically predict the thermo-mechanical response of a two-way CLT slab in fire. It replicates the key phenomena: charring-induced stiffness loss, accelerating deflection leading to failure, and the influence of non-uniform heating (e.g. char fall-off) on the timing of failure. This gives confidence to apply the model to more complex scenarios, such as design optimizations for improved fire performance.

6.5. Development and modelling methodology for two-way composite timber slabs in fire

Modern large open-plan timber buildings face significant fire risks due to exposed timber surfaces, as fully exposed ceilings can accelerate flame spread and elevate heat release rates in compartments [45, 68]. To address this, Chen et al. [147, 171, 172] proposed a mixed timber–insulation composite (MTC) slab design, featuring alternating timber strips and non-combustible insulation on the underside, topped with concrete, as shown in Fig. 6.11a.

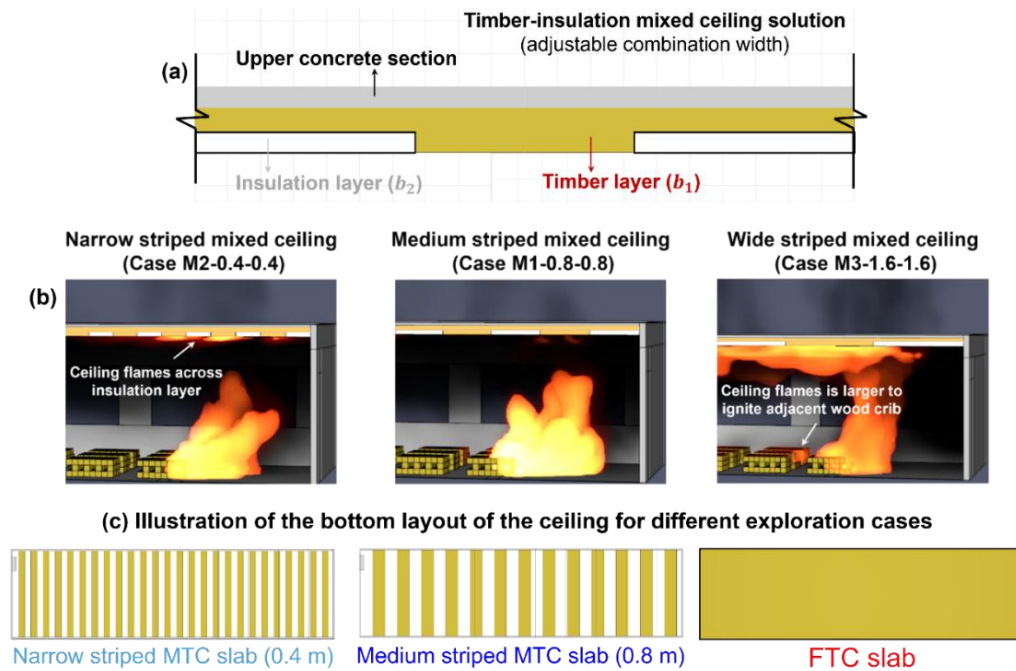


Fig. 6.11. Illustration: (a) Vertical section of the proposed mixed timber composite (MTC) slabs; (b) Effects of ceiling flame inside compartments under different strip widths; (c) Different ceiling slab types used for compartments in the following CFD fire simulations.

The insulation strips compartmentalize the continuous ceiling flames and reduce radiative heat feedback between the adjacent timber strips, mitigating fire spread. The timber to insulation strip width ratio (b_1 / b_2) is adjustable, with equal width strips ($b_1 = b_2 = 0.8$ m) serving as the baseline. Previous CFD studies by Chen et al. [171] evaluated strip width effects: narrow strips (0.4 m) allowed flames to "jump" insulation gaps, while wide strips (1.6 m) intensified localized burning. Medium-width strips (0.8 m) achieve an optimal balance of flame mitigation and strip proportions, as shown in Fig. 6.11b. However, these simulations assumed uniform floor fuel layout, potentially overlooking real-world complexities like clustered fuel layouts. This underscores the need for integrated design strategies to optimize MTC performance under diverse fire scenarios. Studies by Nan et al. [46] highlight that non-uniform fuel arrangements may alter fire dynamics, potentially intensifying localized burning, a phenomenon not captured by uniform-fuel assumptions. Recognizing this issue, a realistic fire scenario incorporating

discontinuous fuel distribution was modelled in a large open compartment. Two MTC slabs with 0.4 m narrow strip and 0.8 m medium strip, and a conventional full-timber composite (FTC) slab with continuous timber underside, as shown in Fig. 6.11c, were investigated under identical conditions. This approach evaluates how insulation widths interact with non-uniform fuel layouts to influence fire spread and structural resilience, providing insights for optimizing MTC designs in practical applications.

6.5.1. Two compartment fire scenarios for exploration

Two compartment fire scenarios were simulated via CFD to generate thermal boundary conditions for structural analysis, as shown in Fig. 6.12. Scenario 1 represents a severe, ventilation-limited fire with a discontinuous and non-uniform fuel distribution, replicating the significant localized burning observed in tests by Nan et al. [46]. The compartment featured a lower window opening (top 0.8 m below the ceiling), restricting smoke exhaust and promoting rapid fire growth with high peak temperatures, which was the worst-case scenario for ceiling slabs. Scenario 2 adopted an optimized design: identical total fuel load but spaced with larger spacing to mitigate fire spread, coupled with higher window opening (top 0.2 m below the ceiling) for enhanced ventilation and faster smoke expulsion. This configuration aimed to mitigate fire development and reduce fire intensity. Both scenarios were applied to three slab types, 0.4 m MTC slab, 0.8m MTC slab, and FTC slab, resulting in a total of six CFD cases. While compartment geometry and fuel load remained consistent within each scenario, the thermal response of the ceiling (slab type) served as the sole variable, enabling direct comparison of fire mitigation strategies under controlled extremes.

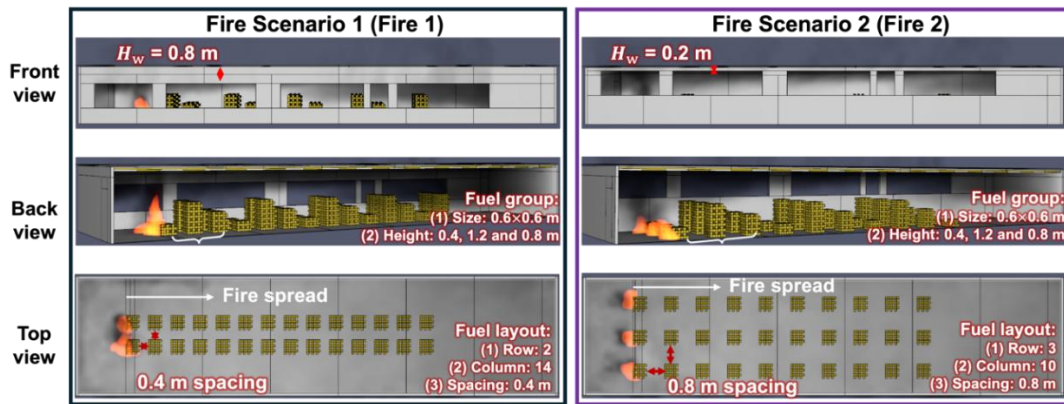


Fig. 6.12. Two different compartment fire scenarios with different settings for following simulations.

6.5.2. Compartment fire behavior results

Table 6.1 summarizes the setup of the six simulation cases (Group 1: MTC 0.4 m, Group 2: MTC 0.8 m, Group 3: FTC; each under Fire 1 and Fire 2). Fig. 6.13a provides a visual comparison of the flame spread development for the different slab types under both scenarios at representative time points. The CFD results revealed markedly different fire behaviors depending on the ceiling design, even with identical fuel and ignition conditions:

Table 6.1. Summary of the setup of exploitation cases.

Cases		Slab type	Fire No.	Spacing between wood crib (m)	Distance from the top edge of windows to the ceiling H_w (m)
Group No.	Case No.				
1	1-1	Narrow striped MTC slab	1	0.4	0.8
	1-2	(0.4 m)	2	0.8	0.2
2	2-1	Medium striped MTC slab	1	0.4	0.8
	2-2	(0.8 m)	2	0.8	0.2
3	3-1	FTC slab	1	0.4	0.8
	3-2		2	0.8	0.2

Under Fire Scenario 1 (limited ventilation, discontinuous fuel), the compartment with a full-timber ceiling (FTC slab) experienced rapid flame spread. Flames quickly spread across the timber ceiling, and the compartment reached full development by 900 s. In contrast, the compartments with MTC ceilings showed a much more localized burning pattern. The fire spread along the ceiling was interrupted by the insulation gaps between timber strips, so large continuous areas of flame did not develop as quickly. The timber strips did eventually ignite beyond the initially involved region, given enough time, the fire can cross the gaps, but the overall rate of fire growth and ceiling involvement was significantly slower than in the FTC case. Thus, the MTC design delayed the fast fire development and limited the peak of flaming during the crucial early stages of the fire, as shown in [Fig. 6.13b](#).

Under Fire Scenario 2 (enhanced ventilation, discontinuous and more dispersed fuel), the fires were generally less severe, as intended by the design modifications. As shown in [Fig. 6.13c](#), strip width had a more significant effect on fire evolution. Both mixed-ceiling configurations continued to mitigate fire spread along the ceiling and effectively reduced peak HRR compared to the full-timber ceiling (Case 3-2). Moreover, the narrow-strip MTC slab (0.4 m, Case 1-2) still outperformed the medium-strip design (0.8 m, Case 2-2), exhibiting a lower and more delayed HRR peak. This indicates that under high-ventilation, widely dispersed fuel conditions, the more frequent insulation gaps in the 0.4 m configuration more effectively segment flame jets and enhance convective cooling, further mitigating fire growth.

In Fire Scenario 2, the superior performance of the 0.4 m MTC slab may be attributed to the combined effects of increased airflow and increased gap frequency. The narrower strips create more containment zones, which, under intense upward smoke flow, prevent small flame plumes from gathering into larger, more intense fires. In contrast, the wider strips in the 0.8 m MTC slab, once ignited, supported larger continuous flame fronts that, while reduced relative to the FTC, produced a slightly higher HRR under the same conditions. These findings emphasize the complex interaction of strip width, ventilation, and fuel layout in determining the fire performance of mixed ceilings. Therefore, in order to optimize MTC design,

it is important to consider the effect of the effects of these factors in real-world fire scenarios to ensure that insulation gaps both interrupt flame paths and facilitate smoke evacuation without inadvertently contributing to the spread of jet-driven fires.

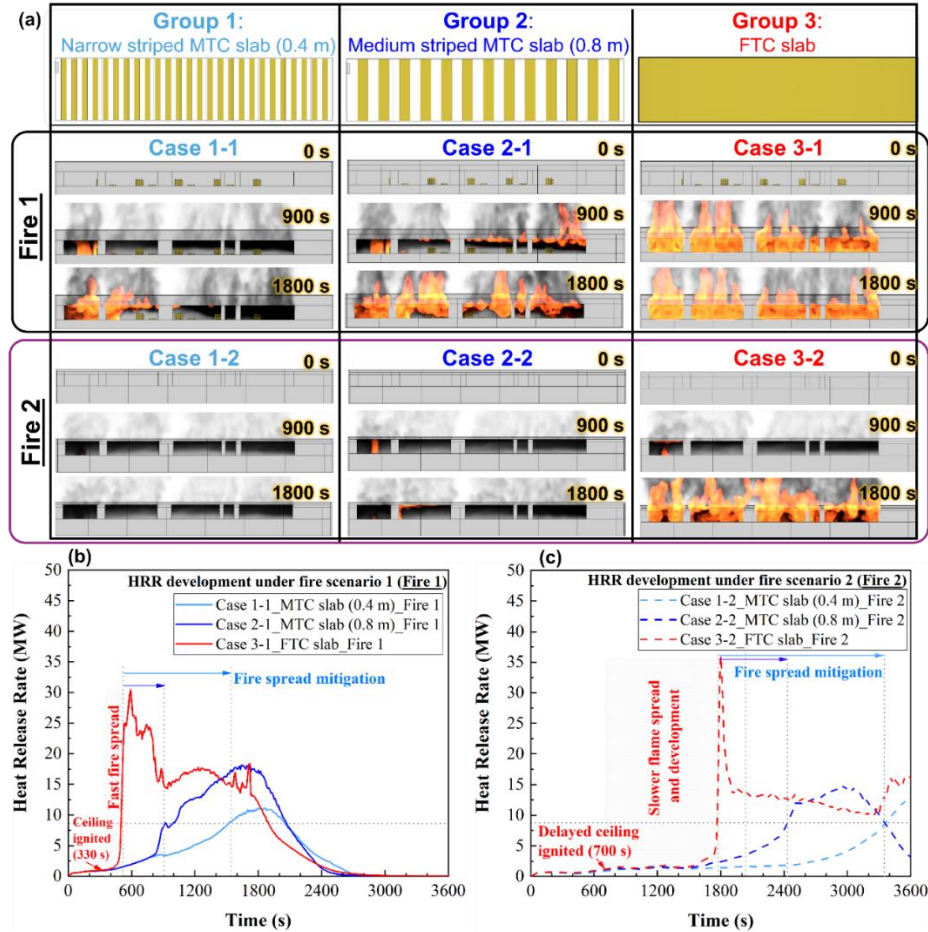


Fig. 6.13. Illustration: (a) Snapshots of compartment fire development from Case 1-1 to Case 1-6 under different fires; (b) HRR vs time under Fire 1; (c) HRR vs time under Fire 2.

6.5.3. Thermomechanical analysis for composite slabs under fire

Based on the established thermal exposure differences between the slab types, the next step was to assess the structural response of the slabs under those fire conditions using OpenSees. Two slab cases for the structural analysis were focused on: the MTC slab with 0.8 m strips (as a representative case from the MTC slab setting, and slightly more critical than the 0.4 m case in terms of fire exposure) and the FTC slab (worst-case, fully exposed timber) as a baseline. These slabs were assumed to be simply supported on four edges, with plan dimensions $4.70 \text{ m} \times 4.00 \text{ m}$, where the widths matched the portion of the compartment ceiling in the CFD model, and the lengths were selected based on the spacing of the potential secondary beam arrangements. Each slab was subjected to a uniformly distributed load of 3.0 kN/m^2 , representing a typical design live load on a floor, which was applied throughout the fire.

6.5.3.1. Comparison of cross-sectional configurations for MTC vs. FTC slabs

To model the cross-section of the 0.8 m strip MTC slab, the enhanced layered shell section formulation (*LayeredShellThermal* V2.0) [32] was employed. This approach accommodates variable cross-sectional geometries by offsetting the reference plane of thicker timber rib regions (100 mm thick) to align with thinner insulated grooves (50 mm thick), ensuring a unified reference plane for shell elements as shown in Fig. 6.14b. The total slab thickness is 150 mm, comprising a 50 mm concrete topping and a 100 mm timber layer beneath, consistent with standard timber-concrete composite designs [173]. However, under the insulation strips (Rockwool CONLIT H80), 50 mm of timber is replaced by non-combustible insulation, leaving only 50 mm of timber in these regions. The concrete and timber layers were explicitly modelled with shell elements, while the insulation was incorporated only in heat transfer analysis due to its non-structural role. Thermal properties of timber (density: 728 kg/m³, moisture content: 11 %) were defined using the *TimberECThermal* material, while the concrete layer utilized the *HTConcreteEC2* model [48].

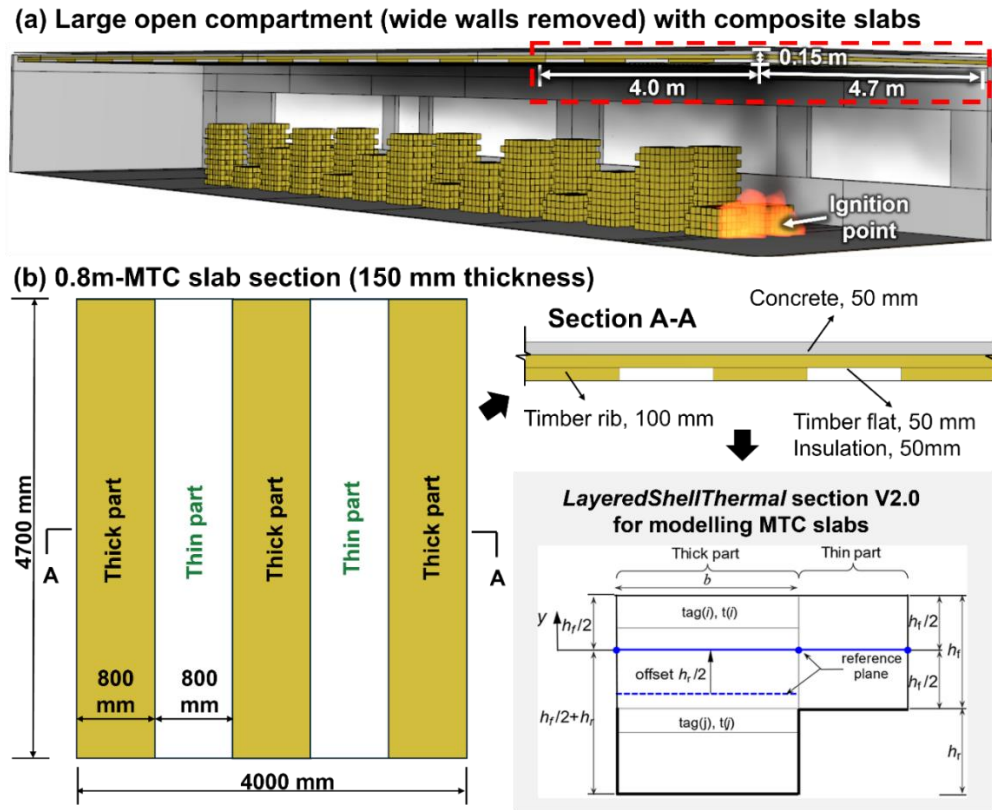


Fig. 6.14. Illustration: (a) Model of compartments equipped with MTC slabs; (b) Bottom-view of MTC slab layout and its cross-section modelling using *LayeredShellThermal* section V2.0 [163].

For the full-timber composite slab, the analysis was simpler. The FTC slab configuration features a continuous 100 mm timber layer beneath the concrete topping, modelled using the standard *LayeredShellThermal* V1.0 section, as shown in Fig. 6.15. Identical dimensions (4700 mm × 4000 mm),

material properties, and boundary conditions were maintained. Heat transfer analysis for the FTC slab required only a single simulation due to its uniform cross-section.

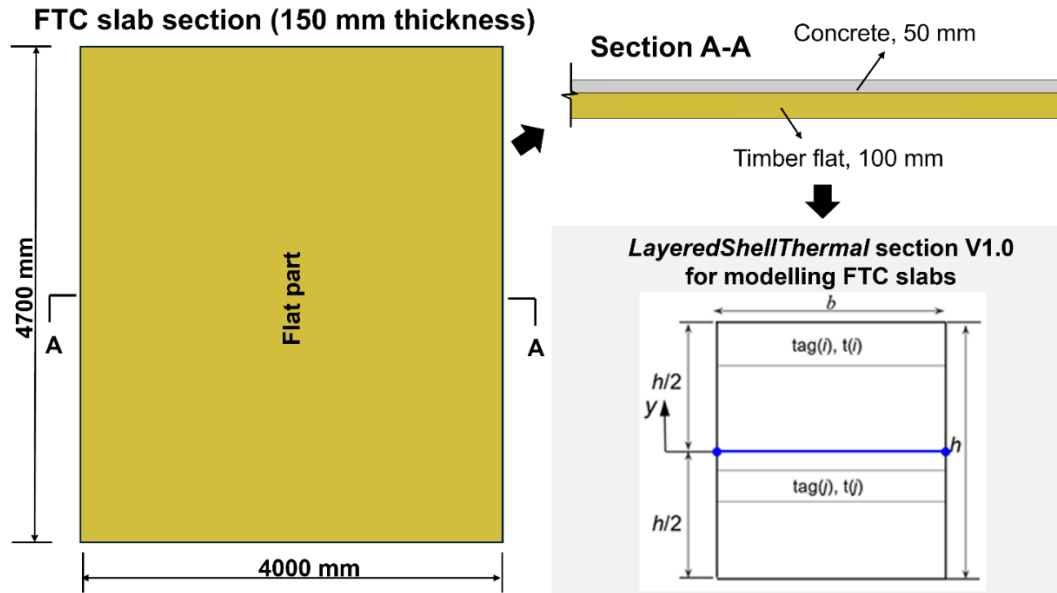


Fig. 6.15. Bottom-view of FTC slab layout used for compartment model and its cross-section modelling using *LayeredShellThermal* section V1.0.

6.5.3.2. Heat transfer analysis for MTC and FTC slabs

For each case, the incident heat flux on the ceiling (as a function of time) obtained from the CFD simulation was applied to the 2D heat transfer model of the slab. The convective coefficient and emissivity were the same as in the earlier validation (25 W/m²K and 0.8, respectively). Two separate heat transfer analyses for the MTC cross-section were performed: one for the timber rib part and one for the timber flat part. In contrast, since the FTC slab has a uniform and continuous cross-section, only one 2D HT analysis was needed for each scenario.

The heat flux history at a representative point near the middle of the ceiling (approximately 2.8 m) was taken and processed through the developed heat transfer model and applied as a boundary condition on the underside of the slab, as shown in Fig. 6.16a. The three heat flux curves described above are tightly coupled with the corresponding 2D temperature plots in Fig. 6.16b: the timing, magnitude, and duration of the incident heat flux directly determine the depth and rate of heat penetration into each slab cross-section. For the FTC slab (red curves), an early, ventilation-limited peak at around 600 s leads to a rapid surface heating that is clearly visible in its cross-section at 1800 s, with almost the entire 25 mm-thick timber layer reaching more than 300°C. In contrast, both MTC schemes avoid this early and rapid development: the corresponding heat flux peak does not occur until about 1800 seconds, and thus the fire exposure of the MTC slabs is much less intense during the initial development phase of the fire.

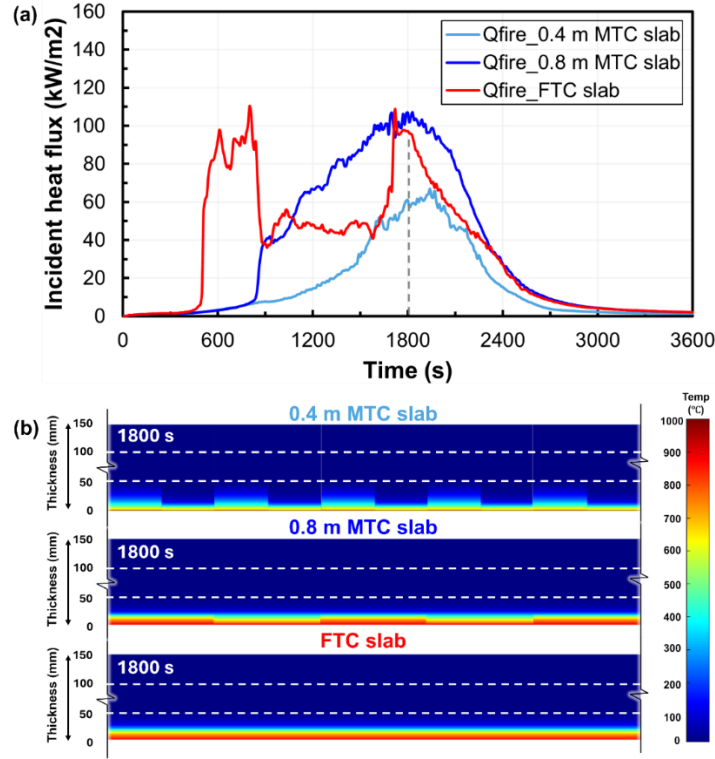


Fig. 6.16. Illustration: (a) Incident heat flux (Q_{fire}) at the boundary of the composite slab from the CFD fire model output; (b) Temperature distribution of the composite slabs at 1800s in Fire 1.

The dark blue curve (0.8 m MTC slab) peaks at 1800 s at about 105 kW/m^2 , while the light blue curve (0.4 m MTC slab) has a lower peak of about 70 kW/m^2 . This difference in heat input is reflected in the temperature plots: at 25 mm of the timber ribs, the 0.8 m MTC slabs reach temperatures close to 260°C , while the narrower 0.4 m slabs (which receive less total energy) only reach about 55°C at the same depth. Underneath the insulated grooves, both MTC solutions had lower temperatures on the exposed side than the timber ribs, demonstrating the insulation's mitigating effect on heat penetration. In addition, the spatial temperature gradient across the MTC cross-section is much greater than that of the FTC slabs: the transition from the hot rib part to the cold flat part occurs only within 40 or 80 mm horizontally, whereas the FTC slabs show an almost uniform profile across the entire width of the slab. In summary, Fig. 6.16a and 6.16b together illustrate that the mixed strip structure critically moderates heat penetration to create a colder protected zone that cannot be created by the FTC slabs. These small heat transfer effects are the basis for the improved fire performance of MTC slabs in the subsequent structural analysis.

6.5.3.3. Comparison of thermomechanical response for MTC vs. FTC slabs

In the structural model for the composite slabs, the concrete layer was modelled with a plane-stress damage-plasticity material (*ConcreteDamagePlasticity*) calibrated to $f_c = 32.1 \text{ MPa}$ (with tensile strength $f_t = 3.2 \text{ MPa}$ and $E = 19260 \text{ MPa}$) and included a nominal steel mesh reinforcement with the yield strength

of 565 MPa to ensure tensile capacity. The timber layer used the same *WoodPlaneStressThermal* material parameters as validated in the CLT slab case. A perfect bond was assumed between concrete and timber (implemented via tying the layers with rigid links). As mentioned before, the slabs were loaded with a UDL of 3.0 kN/m² representing live load and then exposed to the temperature histories from the HT analysis.

Fig. 6.17a plots the mid-span deflection of the slabs over time for each case (FTC slab, MTC 0.8 m, and MTC 0.4 m) under Scenario 1 and Scenario 2, as shown in Fig. 6.17b. The deflection behaviour correlates strongly with the intensity of the compartment fire exposure. The FTC slab deflects the fastest under the severe fire (Fire Scenario 1 with limited ventilation and high fuel concentration). In contrast, both MTC slabs exhibit a slower deflection increase than the FTC slab. The 0.4 m-strip MTC slab performs the best, with the smallest deflection at any given time, while the 0.8 m MTC slab falls in between the 0.4 m and the FTC. Quantitatively, in Fire Scenario 1, the maximum mid-span deflections of the MTC-0.8 m and MTC-0.4 m slabs are approximately 70 % and 52 % of that of the FTC slab, respectively, while in Fire Scenario 2 the corresponding ratios reduce to 55 % and 40 %. These results indicate that the MTC-0.4 m configuration achieves roughly 60 % greater deformation resistance than the FTC slab, confirming the effectiveness of narrower alternating strips in mitigating thermal degradation and structural deflection. This trend corresponds to the fire intensity each slab experienced: the FTC ceiling experienced the most severe heating of the timber, causing the quickest loss of timber stiffness and earlier large deflections. The 0.8 m MTC slab, having larger continuous timber areas, experienced more severe initial localized heating than the 0.4 m case in the non-uniform fuel scenario) and thus suffered greater degradation and deflection than the 0.4 m design.

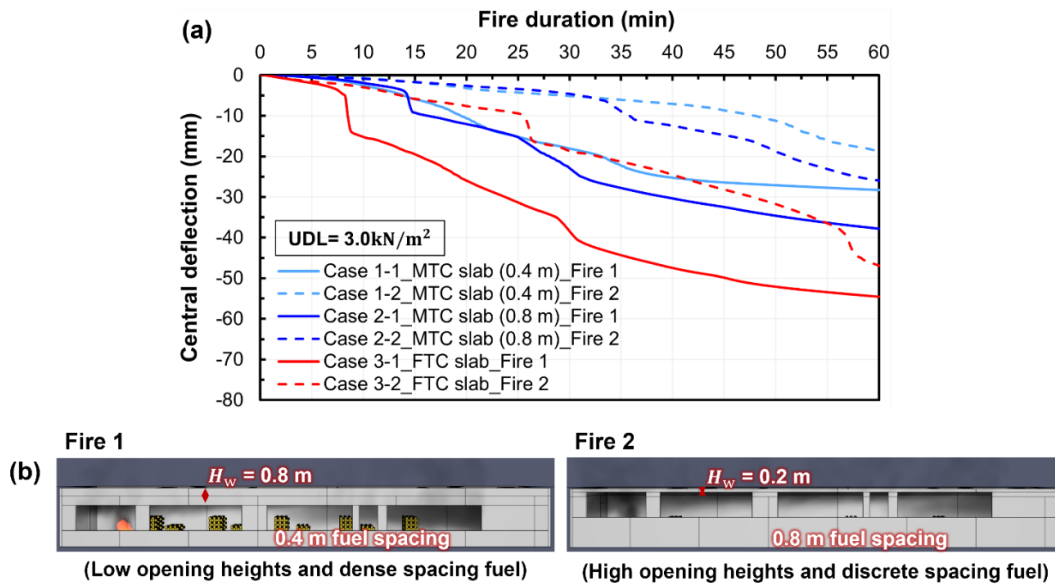


Fig. 6.17. Illustrations: (a) Evolution of mid-span deflection for three slab types subjected to two fire scenarios under the same UDL; (b) Schematic of the two fire scenarios corresponding to Fig. 6.12.

In Fire Scenario 2, characterised by enhanced ventilation and more fuel dispersion, all slabs exhibit markedly smaller mid-span deflections than in Scenario 1, confirming that greater smoke exhaust capacity and clearer fuel spacing mitigate the thermal attack on the structure. The FTC floor slabs are still subject to the fastest and largest deflections, but the margin between FTC and MTC has reduced, highlighting the combined value of enhanced ventilation and clear fuel spacing. A key observation is that the narrow strip MTC slab (0.4 m) now has the least deflection of all configurations, while the 0.8 m MTC slab performs between the 0.4 m MTC slab and the FTC slab. The improved performance of the 0.4m layout can be attributed to its higher frequency of insulating gaps, under stronger airflow, the shorter timber strips limit the sustained formation of flames, accelerating localized cooling and preventing significant heat penetration into the floor core. In contrast, the wider 0.8-m timber strips, while still insulated, have a larger area of continuous timber that absorbs more heat once ignited, resulting in a slightly greater loss of stiffness. This difference suggests that the optimization of MTC ceilings should consider the coupled effects of strip width, ventilation condition, and fuel layout to ensure that the insulation gap is effective in mitigating flames spread in fire scenarios.

Overall, the integrated fire–structure analysis confirms that the MTC slab design provides superior fire performance relative to a traditional FTC slab. The MTC ceiling not only delayed and limited flame spread in the compartment, but also helped the slab maintain its load-bearing function longer by reducing the thermal penetration on critical timber sections. By integrating computational fluid dynamics for compartment fire dynamics with structural analysis in OpenSees for fire, engineers can explore various design parameters (strip width, insulation material, ventilation openings, fuel layouts, etc.) to arrive at robust solutions that ensure both structural integrity and fire spread mitigation.

6.6. Conclusion

This chapter has extended the OpenSees for fire framework to analyze the coupled thermal and structural behaviour of two-way load-bearing timber slabs exposed to realistic fire scenarios. By incorporating an orthotropic plastic-damage material model with real-time stiffness updates and directed damage evolution, the approach captures the distinct material properties of timber in the longitudinal (parallel-to-grain), transverse (perpendicular-to-grain), and in-plane shear directions under fire. The key findings are summarized as follows:

1. A specialized plastic-damage constitutive model was developed for timber to consider brittle fracturing in tension and shear and nonlinear softening in compression. Through segmented linear constitutive laws and temperature-dependent parameter updates, this model captures critical phenomena such as stiffness degradation throughout fire exposure.
2. The timber material model was integrated into a layer-based shell element formulation, enabling

realistic simulation of two-way load-bearing timber slabs under non-standard fire conditions. This thermo-mechanical coupling in OpenSees for fire addresses both the heat transfer and mechanical degradation processes, improving the fidelity of predicted slab deflections and failure modes in comparison to one-dimensional methods.

3. Comparisons with experimental data for a full-scale two-way CLT slab fire test confirmed the model's ability to predict temperature profiles and deflection behaviour up to failure with reasonable accuracy. Moreover, the modeling framework was extended to complex composite floor assemblies featuring a timber-insulation mixed slab, illustrating its potential for evaluating innovative fire-mitigation designs and guiding performance-based fire engineering in large open compartments.
4. Parametric case studies on full timber composite (FTC) and mixed timber composite (MTC) slabs have shown that, under the same conditions, MTC slabs not only mitigate rapid fire spread but also better maintain slab integrity. When combined with optimized ventilation and fuel layout strategies in the compartment, this MTC slab design further improves fire safety, demonstrating a promising approach for enhancing the fire resilience of mass timber floor systems.

Some limitations of the current study should be acknowledged. While the numerical results provide valuable insights into the feasibility and resilience of two-way timber slabs in fire, further experimental validation remains necessary to refine material parameters and validate damage thresholds. Additionally, uncertainty in timber properties, fire exposure conditions, and loading, underscore the need for more comprehensive testing to calibrate and validate the model across different scenarios. Nevertheless, this work advances the modelling of two-way load-bearing timber slabs in fire, offering a reference solution for future studies aimed at establishing reliable, performance-based design guidelines for mass timber floor system exposed to fire.

Chapter 7: Conclusions and Future works

7.1. Conclusions

In alignment with society's growing focus on green and sustainable urban development, timber is increasingly seen as a viable alternative to traditional building materials, offering contributions to carbon reduction goals. To facilitate the safe integration of timber in modern and future constructions, this thesis investigates the potential fire hazards associated with the combustibility of timber in compartment fire scenarios. The study begins with the development of material, heat transfer, and thermo-mechanical analysis models for timber components, based on the OpenSees for fire open-source platform. Additionally, without sacrificing the advantages of using timber, this work also presents a comprehensive study of fire safety design methods accordingly to ensure safe use.

7.1.1. Achievements of research objective

- Development of an enhanced heat transfer model (Chapter 2): The first step was to accurately model the thermal response of timber under realistic, non-standard fire exposures. Chapter 2 introduced a novel heat-transfer model in the OpenSees for fire platform that incorporates temperature-dependent thermal properties of timber and accounts for heat generated by timber combustion. This layered thermal model uses a dual-indicator approach to track both temperature and charring progression through timber sections. It was validated against experimental data from non-standard fire tests, demonstrating that it can reliably predict temperature evolution and charring depth in timber members. By capturing both external heat flux and the internal heat released during timber pyrolysis, this model overcomes the limitations of conventional design methods (e.g. Eurocode 5) and lays a foundation for simulating timber behavior under realistic fire scenarios.
- Integrated thermo-mechanical simulation of timber components (Chapter 3): Building on the thermal model, Chapter 3 established a coupled analysis framework to predict the thermomechanical response of timber structural members during fire. The enhanced heat-transfer model from Chapter 2 was integrated with structural finite element analysis in OpenSees, enabling one to apply temperature histories to timber elements and compute the mechanical behavior during the heating stage. Using this framework, Chapter 3 simulated typical structural scenarios, such as a timber slab with one-sided fire exposure and a glulam beam with three-sided exposure, and validated the results against full-scale fire test data. The OpenSees simulations showed good agreement with experimental observations, accurately reproducing key results like charring evolutions, deflection histories, and time-to-failure of the members by using the appropriate integrator. Furthermore, Chapter 3 demonstrated the versatility of the platform through a preliminary CFD-OPS coupled simulation: thermal outputs from a

computational fluid dynamics (CFD) compartment fire model were applied as input to an OpenSees model of a timber-concrete composite slab.

- Timber-insulation mixed ceiling design for fire mitigation (Chapter 4): To mitigate the rapid fire spread typically associated with exposed timber surfaces, Chapter 4 introduced the timber-insulation mixed ceiling strategy in which the strips of non-combustible insulation material are mixed with timber strips on the bottom surface of the ceiling, aiming to reduce the initially exposed timber surface and limiting the preheating effect to adjacent timber strips. A variety of CFD fire simulations were performed to validate this design, using a baseline model calibrated against the Malveira fire test. The simulations compared three ceiling configurations: a full timber (FT) ceiling, the proposed mixed timber-insulation ceiling, and a full-protection (FP) ceiling. The mixed ceiling proved highly effective in mitigating fire growth, which reduced the flame spread and peak heat release rates compared to the full-timber ceiling case. Notably, for approximately the first 30 minutes of the fire, the compartment with the mixed ceiling exhibited fire dynamics comparable to those in the full-protection ceiling case.
- Evaluation of realistic scenarios and design suggestions (Chapter 5): To ensure the proposed strategy remains effective under real building conditions, Chapter 5 expanded the investigation to more complex and realistic compartment scenarios. A series of parametric CFD simulations examined how various realistic factors influence fire development in a large timber compartment featuring the mixed ceiling. The factors studied included non-uniform fuel load distributions, the presence of different structure beams, different window opening heights, and challenging ignition locations. The results provided important insights for performance-based fire design. It was found that assuming a uniformly distributed fuel load as is common in traditional test design can dangerously underestimate the intensity of a fire. Similarly, the ceiling beam layout was shown to influence flame spread, as beams can obstruct smoke flow and intensify the localized fire. Ventilation conditions also played a crucial role: for instance, higher window openings allowed hot smoke to vent out earlier, which in turn reduced smoke accumulation under the ceiling and mitigated the lateral spread of flames. Across these varied scenarios, the timber-insulation mixed ceiling consistently performed robustly. Even in high-severity cases with a fuel concentration and limited ventilation, the mixed ceiling design mitigated fast fire spread, maintaining fire growth rates comparable to case with full-protection ceiling for 30 minutes. Additionally, Chapter 5 explored optimizations to the mixed ceiling concept inspired by a “cabin” compartmentalization approach, suggesting that strategically zoning can further enhance fire performance under a challenging fire with higher risk ignition point.
- Updated modelling for two-way timber slabs (Chapter 6): To extend the simulation capabilities to more complex structural elements, Chapter 6 developed an orthotropic damage-plasticity constitutive model

for two-way timber slabs. Implemented in OpenSees for fire, this material model captures the anisotropic mechanical properties of timber and their degradation at elevated temperatures, including brittle failure in tension/shear and strength reduction in compression as heating progresses. Chapter 6 validated this updated model against a full-scale fire test on a two-way CLT slab, showing that the numerical simulation closely reproduced the slab's observed deflection behavior and failure time. Building upon this framework, and in response to the second research question concerning the mitigation of fire spread, a composite slab incorporating the proposed timber-insulation mixed ceiling design was introduced. In this chapter, the coupled thermomechanical response of this system was demonstrated through an integrated CFD-OPS, enabling a sequential assessment of its performance under realistic compartment fires. The results indicated that the composite slab with a timber-insulation mixed ceiling experienced substantially smaller deflections and a slower temperature rise in its timber layers compared to a traditional all-timber slab under the same fire exposure. Quantitatively, the mixed-ceiling composite slab's mid-span deflection at failure was only about 40-70 % of that of a fully exposed timber slab, highlighting a significant improvement in fire resistance.

7.1.2. Significance and limitations of the current research

Significance: This research provides both scientific and practical contributions toward the fire-safe use of timber in modern construction. By advancing an open-source simulation platform (OpenSees for fire) with new heat-transfer and constitutive models for timber, the work enables to more accurately predict how structural timber members will behave in realistic fire scenarios. Such capability is crucial for performance-based fire safety design, where designers must demonstrate that buildings remain safe under credible fire conditions rather than just following prescriptive codes. The thesis also offers an innovative fire protection solution, the timber-insulation mixed ceiling, which balances architectural aesthetics and sustainability against safety needs. This design concept, validated through extensive simulations, could be adopted in modern buildings to mitigate rapid fire spread, thereby protecting occupants and property while still allowing the use of exposed timber for its environmental and structural benefits. Collectively, the outcomes of the five research objectives form a coherent strategy that supports the wider application of mass timber in green architecture, providing confidence that the associated fire risks can be effectively managed with appropriate engineering measures.

Limitations: Notwithstanding its contributions, the study has some limitations that should be acknowledged. First, many of the findings are based on numerical simulations and would benefit from further experimental validation. For example, the heat-transfer model developed for timber material in Chapter 2 was validated against specific laboratory fire tests and its performance in other fire scenarios (e.g. different timber species or scale) may vary, and scaling up to real structural systems could introduce complexities (such as char fall-off or 3D heat transfer effects) not fully captured by the model. Moreover,

while the present validation cases primarily involved solid timber, CLT, and Glulam, the applicability of the proposed modelling framework to other engineered wood products such as laminated veneer lumber (LVL) or scrimber requires further study. These materials exhibit more complex thermal and mechanical behaviours because their performance is influenced not only by the base wood species but also by adhesive systems, veneer orientations, and interfacial bonding between layers. Therefore, although the current layer-based and orthotropic constitutive formulations provide a transferable foundation, reliable application to LVL or scrimber would require additional experimental calibration and parameter characterization. Similarly, the coupled structural fire analyses in Chapter 3 were demonstrated on idealized cases (single elements and a preliminary composite slab study). While the simulation results matched available test data, the approach has not yet been applied to a wide range of structural configurations or long-duration fires, which might reveal additional challenges (like connection failures) beyond the current scope. The fire mitigation strategy studied in Chapters 4 and 5, the mixed ceiling design, was evaluated using CFD models under controlled conditions and assumptions (e.g. specific compartment size, fuel types, and ideal insulation materials). There is an inherent uncertainty in how such a design would perform in a real building fire and factors like construction quality, material variability, or unforeseen ignition scenarios could affect its efficacy. Additionally, the compartment fire simulations, although extensive, did not cover every possible scenario, for instance, multi-compartment interconnected fires, or sprinkler interventions were outside the scope. Each parameter investigated (fuel distribution, ventilation, etc.) was varied individually, so their combined effects in a complex real building environment remain to be studied. Finally, the two-way slab model in Chapter 6, while advanced, is subject to the limitations of material modelling assumptions and the quality of available test data. The model currently assumes uniform material properties and ideal bonding in composite action. However, in practice, issues like delamination between timber and concrete at high temperatures or variability in timber lamellae could influence structural performance. In summary, the conclusions drawn in this thesis are robust for the conditions examined, but caution is advised when generalizing them. Further research, including full-scale fire tests, more diverse case studies, and refined modelling of complex phenomena, is recommended to extend the validity of these findings and to address the noted limitations for safer implementation in engineering design.

7.2. Future works

As the world progressively moves towards carbon neutrality, the development trend of timber structures is expected to continue advancing. However, the fire performance and design of wood as a building material remain an emerging and pressing issue in combustion science, fire dynamics, and structural fire resistance research. Although existing studies have highlighted the potential fire safety risks of timber structures, current research findings are insufficient to provide a solid foundation for regulatory bodies, nor do they fully alleviate the concerns of designers when extensively using timber. Therefore,

facing the widespread application of timber in high-rise buildings, modular construction, and composite structures as shown in Fig. 7.1a, 7.1b and 7.1c, and the urgent need for more in-depth research support for modern fire protection design, a mind map of the potential future research framework based on the current research is shown in Fig. 7.1d, and will be clarified in detail on the following sections as well.



Fig. 7.1. Illustration of current timber application in construction: (a) Commons Tallwood House in Vancouver, Canada [174]; (b) Timber used for modular construction [175]; (c) Timber slabs built with 3D printed concrete structures [176]; and (d) Mind maps of the potential future research framework.

7.2.1. Experimental fire research of proposed mixed ceiling design on real building scales

As shown in Fig. 7.2, the highest priority for future work is full-scale experimental validation of the timber-insulation mixed ceiling design under realistic compartment fires. While Chapter 4 demonstrated through CFD simulations that alternating non-combustible insulation strips with timber strips can significantly mitigated fire spread (achieving fire behavior comparable to a non-combustible ceiling for up to 30 minutes), these findings rely on numerical models. There is an urgent need to conduct full-scale compartment fire tests in real buildings to verify the fire mitigation performance of the proposed mixed ceiling design in practice. In particular, tests must cover a range of ventilation conditions and fuel load layouts to reflect worst-case and typical building contents. Therefore, planned tests should include both

ventilation-limited scenarios and well-ventilated scenarios, as well as both uniform fuel distributions and highly uneven fuel concentrations, to evaluate the mixed ceiling's efficacy under each condition. Observing the mixed-ceiling's performance in these settings will confirm whether the proposed design consistently mitigated flame spread in real fires, as anticipated by simulation. Such experiments will also provide invaluable data to refine fire models and to build credibility with regulators and designers who require empirical evidence of safety.

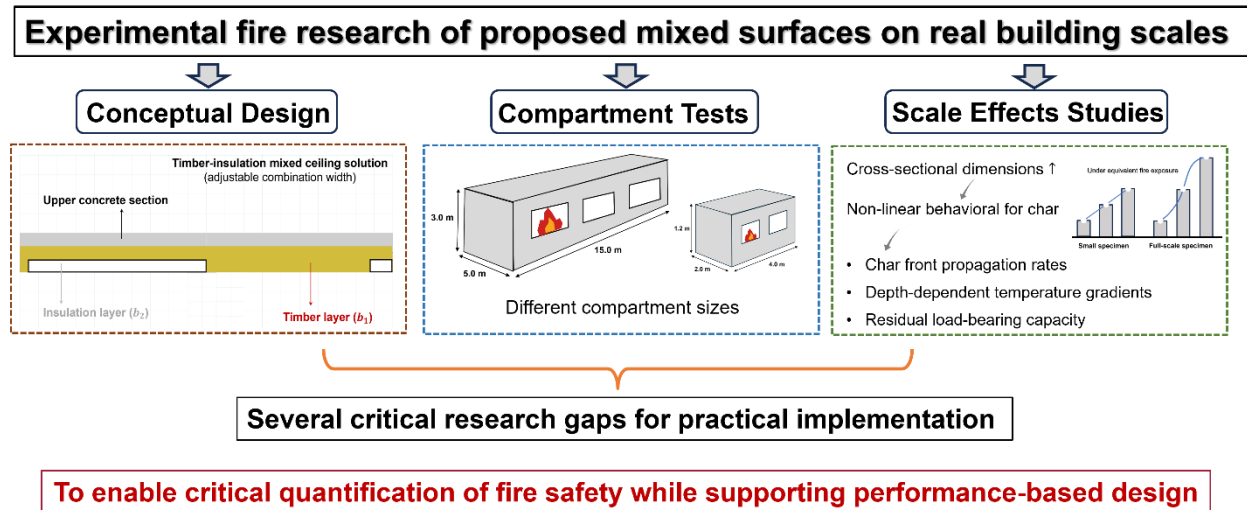


Fig. 7.2. Experimental fire research of proposed mixed ceiling design on real building scales.

Another research need is to investigate scale-dependent fire behavior of the timber-insulation mixed ceiling. Small-scale tests or simulations may not capture phenomena that emerge at realistic scales. For instance, as structural dimensions increase, the timber's charring and heat transfer behavior can become non-linear due to thicker sections forming deeper char layers with insulating effects. Chapter 6 identified that the MTC slab dramatically reduced mid-span deflections compared to a full-timber slab in simulations (only about 40-70% of the deflection of a conventional FTC slab). However, these results were obtained using models validated against standard tests on smaller specimens. Full-scale compartments and structural members could respond differently, e.g. char front progression, temperature gradients through the timber depth, and residual load capacity may all vary with scale. Systematic studies should compare results from mid-scale vs. full-scale compartment fire tests to quantify these effects. For example, a series of tests in rooms of increasing size (with identical ceiling designs and fuel loads) would reveal how fire growth and timber charring evolve as room size grows. Important metrics include the char rate and profile in the timber strips, the temperature distribution across the composite slab thickness, and the time to structural failure or excessive deflection. By measuring these in real fires, researchers can identify any scale-related discrepancies from current models. If the mixed ceiling's effectiveness diminishes (or improves) in larger compartments, that insight will guide necessary design adjustments. Overall, this experimental program

encompassing various compartment sizes, ventilation rates, and fuel configurations represents the most critical step in validating the fire mitigation strategies proposed in the thesis under realistic conditions. It will either confirm the robustness of the mixed ceiling design or highlight any limitations, thereby providing a solid foundation for performance-based fire design guidelines for timber buildings.

7.2.2. Optimized design for mixed exposed surfaces under uneven fuel distribution scenarios

In addition to conceptual validation, future research should optimize the timber-insulation mixed ceiling design for uneven fuel load scenarios, which are common in real buildings. Chapters 5 and 6 revealed that non-uniform distribution of combustibles can significantly influence fire spread, and concentrated fuel in a single area can lead to intense local burning and faster flame propagation. In practice, furniture and objects are rarely spread uniformly across a floor; there may be clusters of high fuel density (such as storage areas or workstation groups) interspersed with sparser regions. These uneven layouts can produce non-linear fire behaviors, as flames rush toward fuel-rich zones and possibly create travelling fire conditions. To design resilient timber compartments, the mixed ceiling configuration may need to be tailored to the fuel distribution risk profile. Future work should investigate how varying the pattern or proportion of insulation strips in the ceiling can compensate for uneven fuel loads. For instance, regions of the ceiling above high-density fuel zones could incorporate a greater fraction of non-combustible strips (or additional protective coatings), whereas areas above low-fuel zones might allow more exposed timber. This adaptive approach would effectively create a spatially optimized ceiling that anticipates where severe burning is likely to occur. In Chapter 5, an initial attempt at optimization (inspired by a “cabin concept”) demonstrated that strategically arranging the strips combination can sustain fire development at levels comparable to a fully non-combustible ceiling for up to 30 minutes. Building on this, researchers should perform parametric fire studies and targeted experiments with different fuel layouts to identify the optimal ceiling strip configurations. Key variables include the strip width, spacing frequency of insulation gaps, and possibly the layout of timber vs. insulation strips in relation to expected furniture arrangements.

To systematically handle the complexity of uneven fuel scenarios, data-driven and computational techniques will be invaluable. One promising direction is to use machine learning (ML) and pattern recognition to generalize fire spread behavior under various fuel distributions. A large dataset could be generated from CFD simulations and mid-scale fire experiments where the fuel arrangement is systematically varied (e.g. clustered vs. dispersed vs. random placements of wood cribs or furnishings). By training ML models on these scenarios, it may be possible to predict how a given fuel layout will influence the flame spread rate and intensity. For example, an ML framework could identify critical thresholds of fuel clustering that lead to rapid ceiling ignition, or recognize spatial patterns associated with slower fire growth. With such predictive capability, designers could then optimize the mixed ceiling design using algorithmic approaches: the ML model would serve to evaluate candidate ceiling configurations against many possible

fuel arrangements, flagging configurations that minimize worst-case fire spread. Future research should develop this into an optimization tool that suggests the best combination of timber and insulation strips for a given occupancy's fuel distribution profile. In essence, this would be a smart, risk-informed design method: rather than a one-size-fits-all ceiling, the timber-insulation pattern can be adjusted according to the expected fire load distribution. Combining those insights with the mixed ceiling concept could yield a highly effective mitigation strategy even in challenging uneven-fire scenarios. Ultimately, this line of research will produce guidelines or algorithms for site-specific ceiling design, ensuring that timber use in ceilings remains safe regardless of how occupants arrange combustibles in the space, as shown in Fig. 7.3.

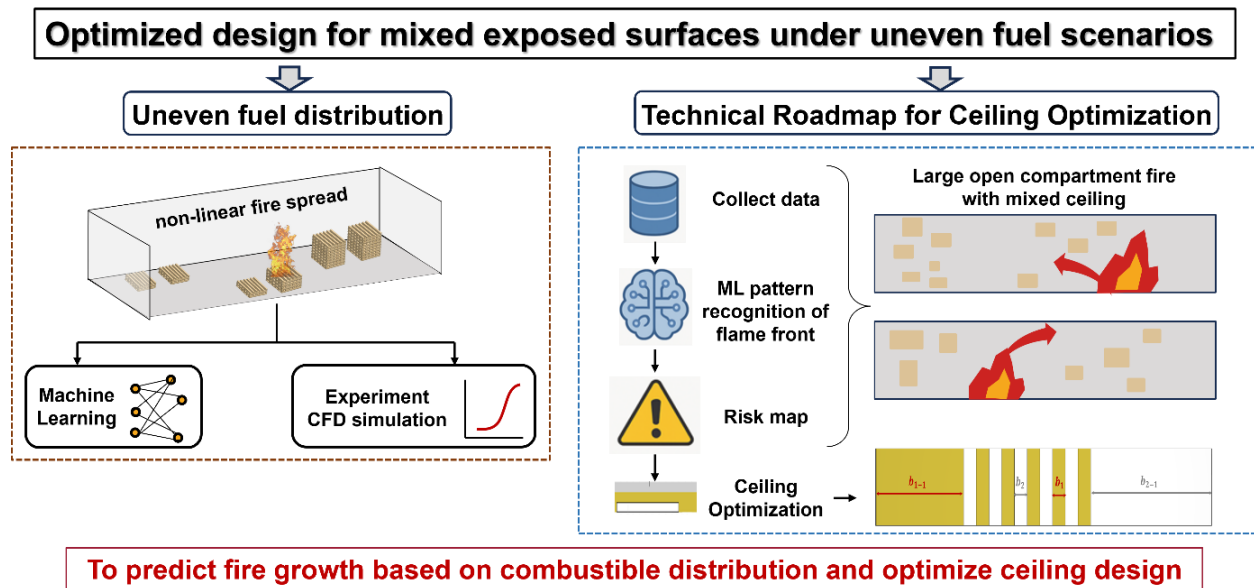


Fig. 7.3. Optimized design for mixed ceiling design by using machine learning for predicting the fire spread under uneven fuel scenarios.

7.2.3. Performance-based design tool for composite floor slabs with mixed ceiling design

Another important future direction is the development of a performance-based design toolkit for composite timber floor slabs featuring the mixed ceiling design, as shown in Fig. 7.4. Chapters 4-6 introduced an integrated simulation approach where fire dynamics from CFD models were coupled with structural analysis in OpenSees to evaluate the MTC slab's behavior. This combined CFD-FE framework proved capable of capturing the thermomechanical response of the slab under specific fire scenarios and demonstrated clear benefits of the mixed design (e.g. lower deformation and delayed failure compared to a traditional timber slab). However, in its current state, this approach was applied to only a few discrete cases. To make these findings practical for engineering design, a more generalized, parametric study is needed, exploring a broader range of design parameters and fire scenarios. Future research should expand the simulation program to cover variations in timber thickness, insulation strip width, connection details

between timber and concrete, different compartment sizes, fuel loads, and ventilation conditions. By running hundreds or thousands of CFD-assisted thermo-structural simulations, one can map out how each parameter affects two key performance indicators: (1) the compartment's fire dynamics (e.g. peak heat release rate) and (2) the structural response (e.g. maximum deflection, time to failure of the slab). The aim is to derive quantitative relationships or design charts that relate slab configuration and fire conditions to outcomes like flame spread rate and structural stability. These insights would form the basis of a performance-based fire safety design methodology, allowing engineers to predict how a proposed floor design will behave in a fire and adjust it to meet safety criteria.

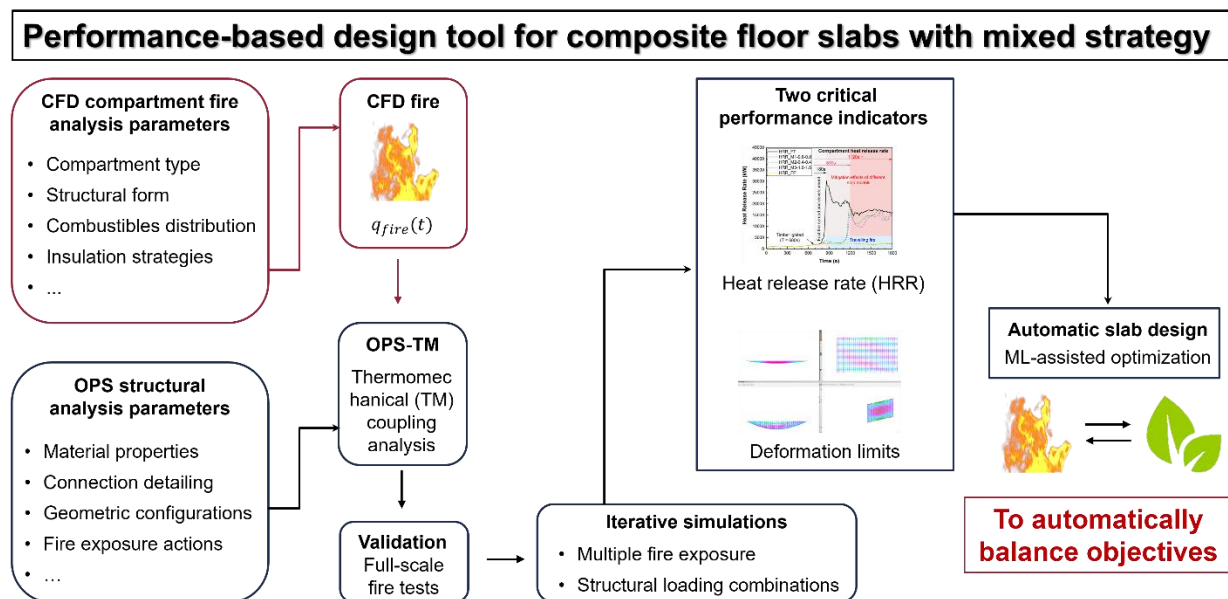


Fig. 7.4. Performance-based design tool balancing the fire performance and sustainability for composite slab system with - design.

To make this capability accessible and efficient, the extensive simulation results should be refined into a software tool or design guide. One approach is to utilize machine learning or alternative models to create fast-running predictive models based on the simulation data. For instance, a trained alternative model could instantly estimate the expected faster fire spread time and slab deflection given input parameters (timber strip width, compartment size, fuel load, etc.), bypassing the need for a full CFD/FE run. Such a tool could then be used in an optimization loop: automatic algorithms vary the design (timber-insulation pattern, material choices, etc.) to find an optimal solution that balances fire performance and other objectives (like material cost or sustainability). This was mentioned at in Chapter 6, where the concept of balancing fire resistance with sustainability (minimizing non-combustible material use) was discussed. The intended performance-based design toolkit would, for example, allow a designer to input the specifics of a building (room geometry, expected fuel load, structural loads, etc.) and receive recommendations on the ceiling

configuration that achieves required fire safety margins while maximizing timber usage. As part of future work, this toolkit must be validated against experimental results to ensure reliability. After calibrating the simulations with the real fire tests from Section 7.2.1, the final step would be to verify that the tool's predictions match outcomes in additional full-scale fire experiments or large-scale furnace tests for composite slabs. Only after such validation can the tool be confidently used in practice. In summary, this research direction merges computational modelling with design optimization to create a performance-based fire design framework. It directly addresses a limitation of the current thesis work, the lack of a general design method, by translating the simulation findings into a usable form for engineers. This will help bridge the gap between theoretical fire modelling and real-world design of mass-timber buildings, enabling safe yet efficient use of timber–concrete composite slabs with mixed ceilings in future construction.

7.2.4. Combined effects of timber and other building materials

The final proposed research direction is to investigate the combined performance of timber with other materials in composite structural systems under fire, and to establish criteria for post-fire repair. In modern timber construction, floor systems often consist of timber-concrete composites (e.g. CLT panels topped with concrete or connected via steel fasteners) to achieve structural efficiency. The thesis so far has primarily focused on the timber portion and treated the composite action with concrete in an idealized way. For instance, the structural models assumed a perfect bond between timber and concrete layers, with no slip or delamination at the interface during fire. This is an oversimplification, as real interfaces can degrade under heat.

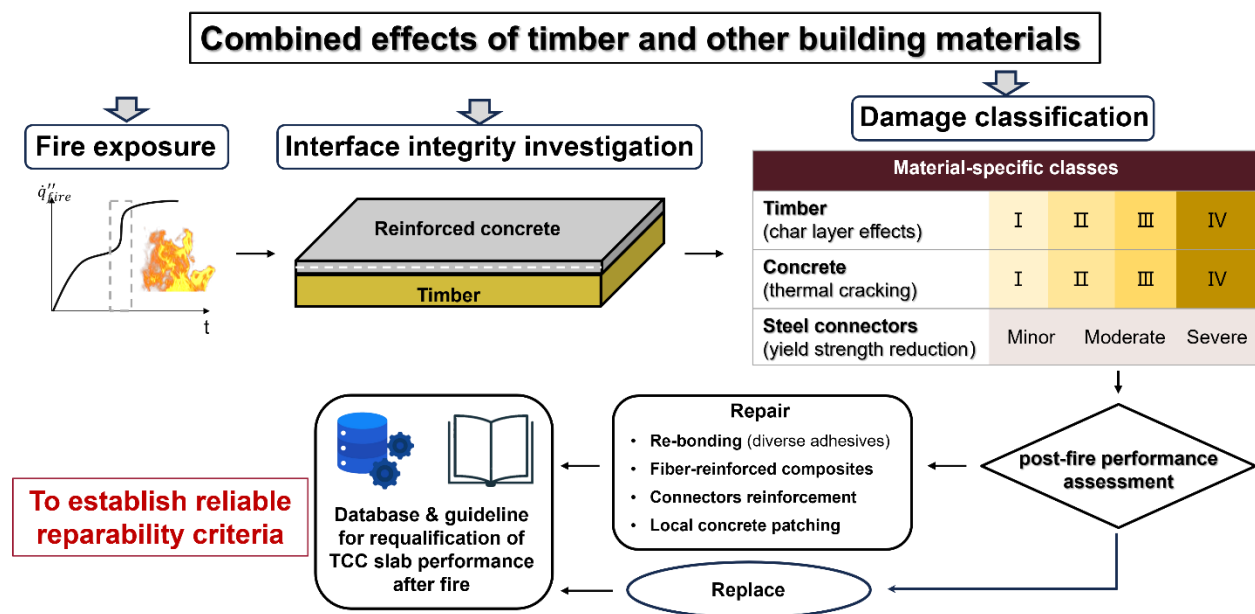


Fig. 7.5. Investigation of the combination between the timber and other building materials and establishment of post-fire repair criteria.

Future work should thus address several interrelated issues to ensure a holistic understanding of fire behavior in timber composite systems, as shown in Fig. 7.5:

- Thermomechanical interaction:
Investigate how timber, concrete, and steel connectors interact under elevated temperatures. Experiments on composite slabs under one-sided fire exposure should clarify how load sharing and deformation evolve as materials degrade. These findings will improve multi-material modelling accuracy.
- Interfacial bonding performance:
Examine the fire endurance of the timber–concrete interface, including adhesives, screws, and notched joints. Tests should quantify bond strength loss and guide the development of fire-resistant interface materials or details to ensure reliable composite action during fire.
- Post-fire residual capacity:
Establish standardized methods to assess residual strength of fire-exposed composite members. Non-destructive evaluation (e.g., ultrasonic or thermal imaging) and mechanical testing can provide data to develop quantitative criteria for post-fire reuse or replacement decisions.
- Repair and reinforcement techniques
Explore practical repair strategies, such as FRP strengthening, steel plate reinforcement, or infill replacement, for damaged timber-concrete members. Experimental studies comparing repair efficiency will support guidelines for safe and economical post-fire rehabilitation.

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