CFD representations of travelling fires – from crib to compartment scale

Structures in Fire Forum

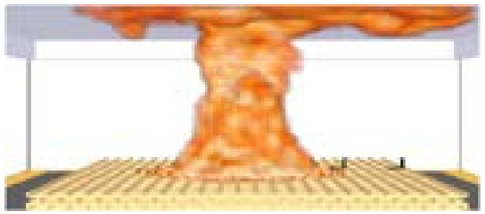
12 May 2023

The Nucleus, The King's Buildings,

School of Engineering, University of Edinburgh



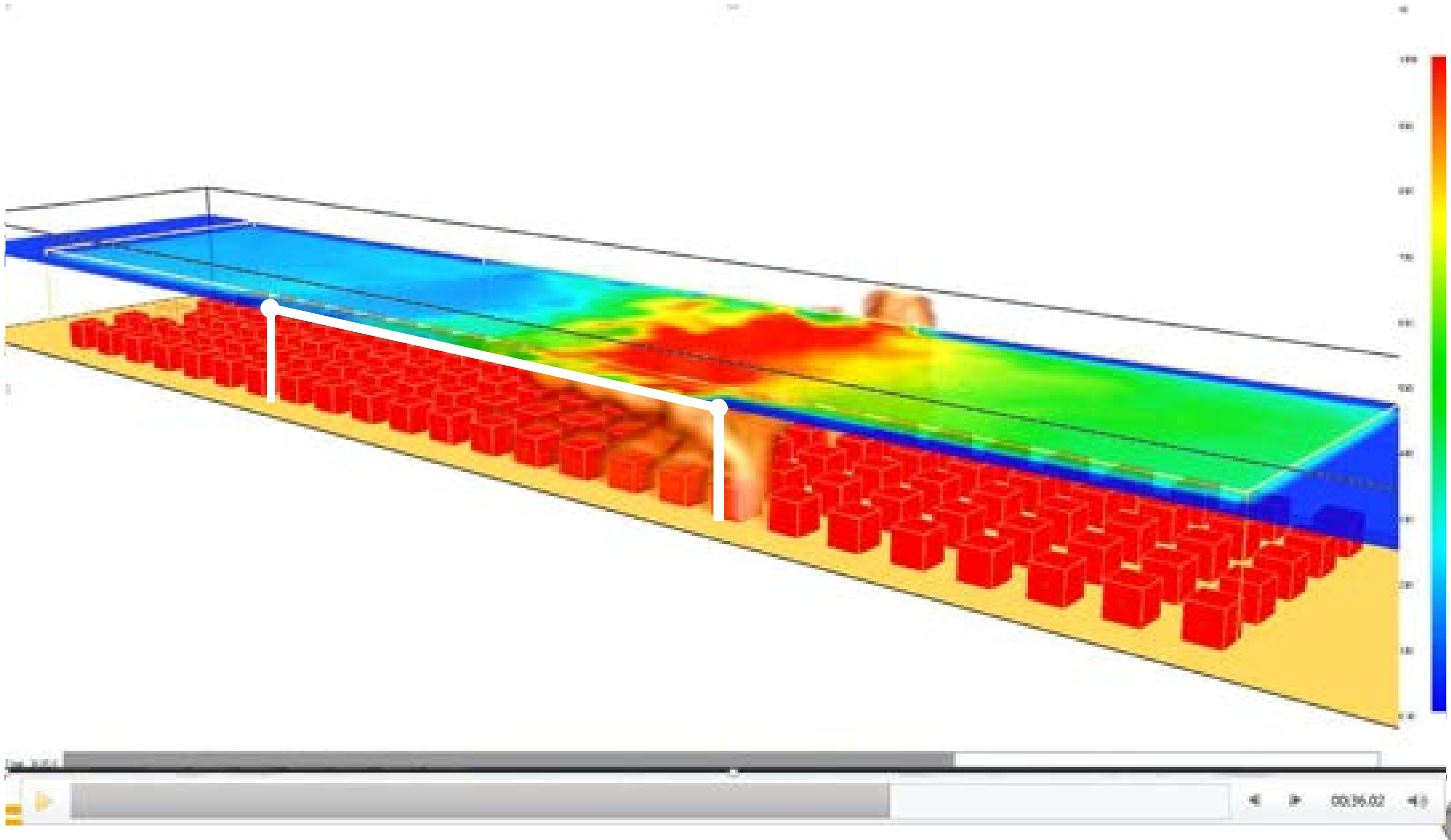
Xu Dai, Chang Liu, Stephen Welch



THE UNIVERSITY *of* EDINBURGH

United Kingdom

Travelling fires for structures



Charlier, M., Vassart, O., Gamba, A., Dai, X., Welch, S. & Franssen, J.-M. (2018) “CFD Analyses Used to Evaluate the Influence of Compartment Geometry on the Possibility of Development of a Travelling Fire”, SiF 2018, University of Ulster, 6-8 June 2018

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Jose Torero*, Scaling-Up Fire:

"The link between refinements in the combustion processes involved in fire modelling and the potential improvements in a fire safety strategy is generally blurred by the complexity of the processes involved, the natural incompatibility of time and length scales and the unavoidable scenario uncertainty. **In this context the use of CFD as a basis for the Scaling-Up of fire has a very clear gain**.

Torero, J.L. (2013) "Scaling-Up Fire", Proc. Comb. Inst. 34: 99-124

Research method

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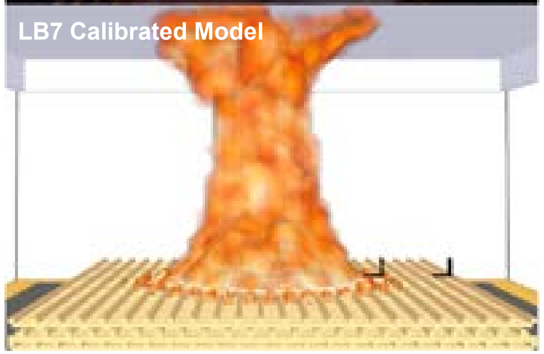
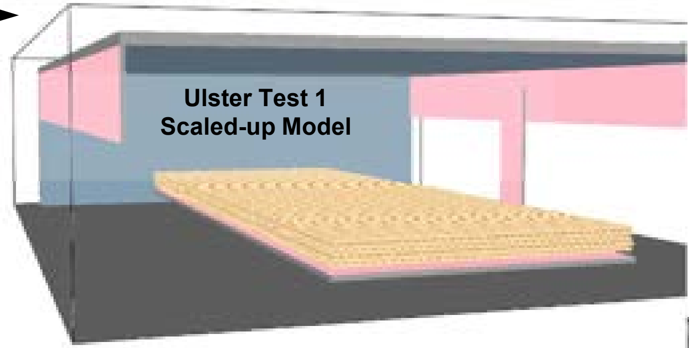


“Scaling-up”

All CFD model parameters remain the same except for compartment info



Crib fire experiments

* Gamba, A., Charlier, M. & Franssen, J.-M. (2020) "Propagation tests with uniformly distributed cellulosic fire load", Fire Safety Journal 117, 103213 doi:10.1016/j.firesaf.2020.103213

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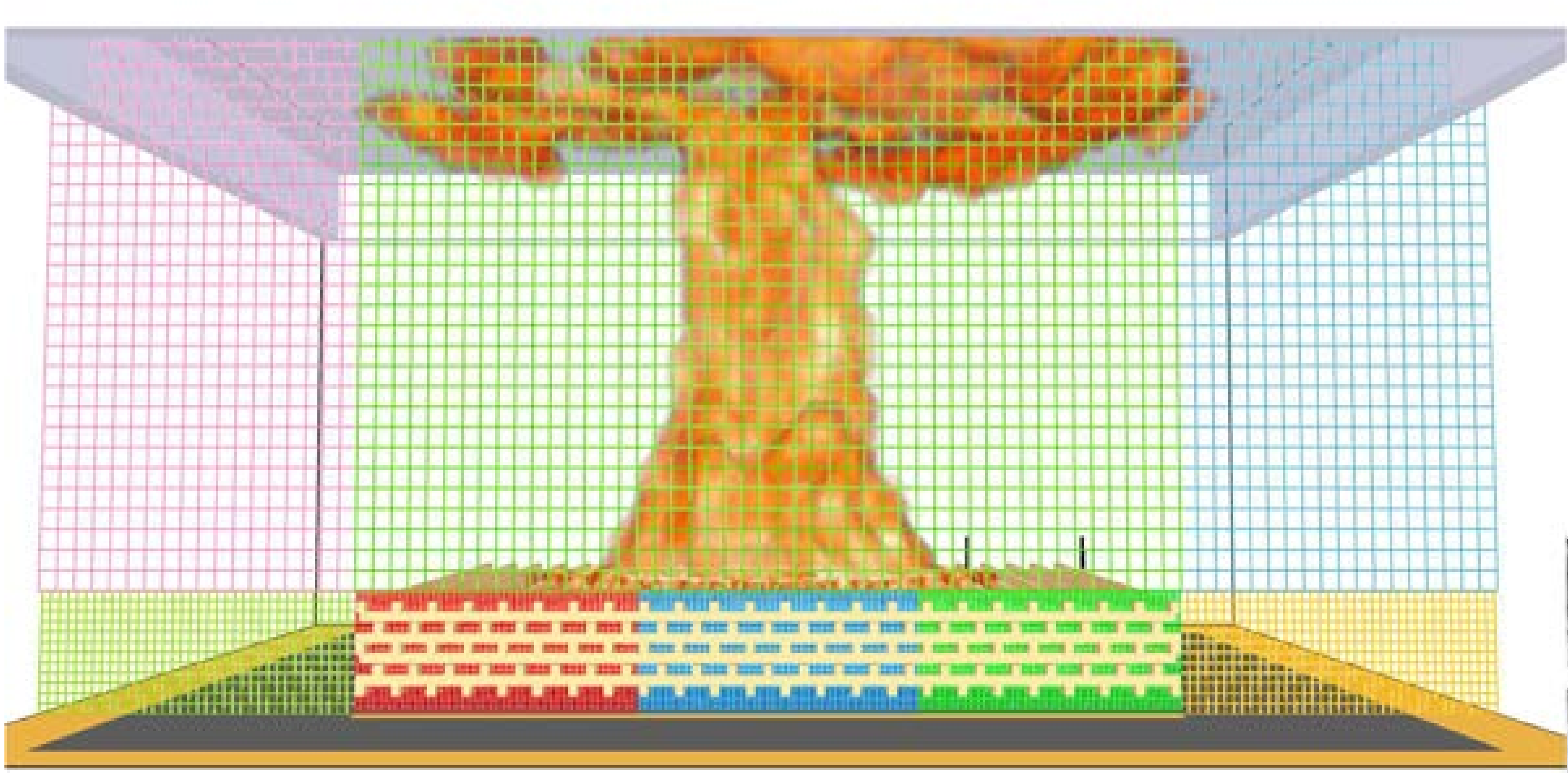
“Liege test series”, LB7 Test, Marchienne, Belgium, 2018

- **Experimental arrangement**

(a) Skewed view of test rig without wood sticks, and (b) Side view of test setup.

FDS modelling for calibration, “Liege test series”, LB7*

- **Grid cell resolution in elevation view**

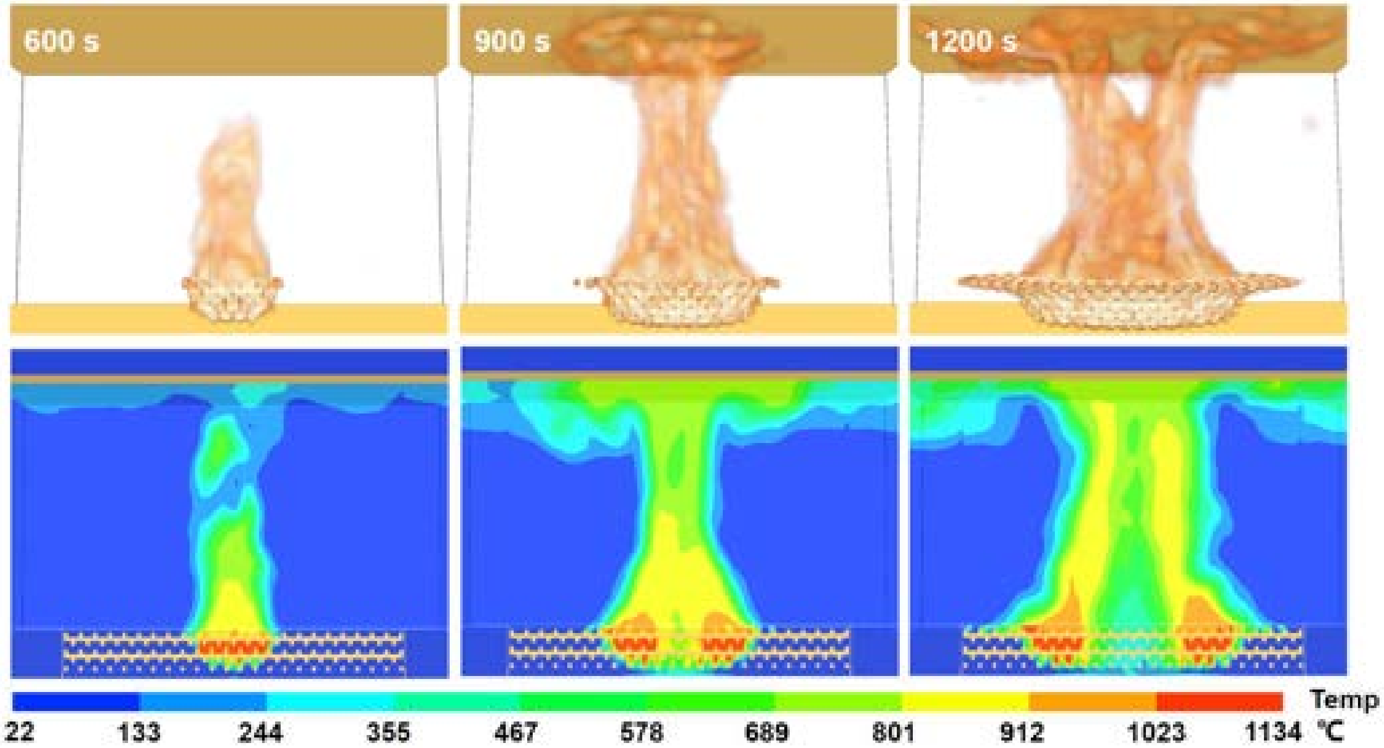


Grid cell resolution of the model: 1.5 × 1.5 × 1.75 cm per cell for wood sticks in porous crib structure, 6 × 6 × 7cm and 3 × 3 × 3.5 cm cell size in gas phase, total no. cells ~1.3 million.

* Dai, X., Gamba, A., Liu, C., Anderson, J., Charlier, M., Rush, D. & Welch, S. (2022) “An engineering CFD model for fire spread on wood cribs for travelling fires”, Advances in Engineering Software 173:103213 https://doi.org/10.1016/j.advengsoft.2022.103213

FDS modelling for calibration, “Liege test series”, LB7

- Fire development within the wood crib
- Temperature development within the wood crib



(a) Flame development within wood cribs (wood sticks “obstruction” removed in Smokeview for clearer flame demonstration), and (b) Temperature development at the compartment central ‘slice’.

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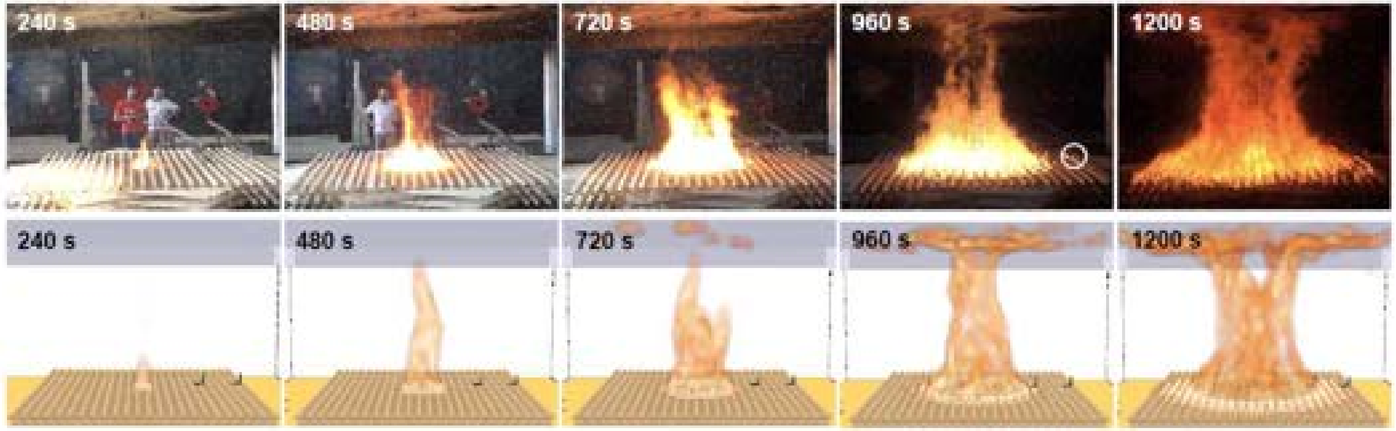
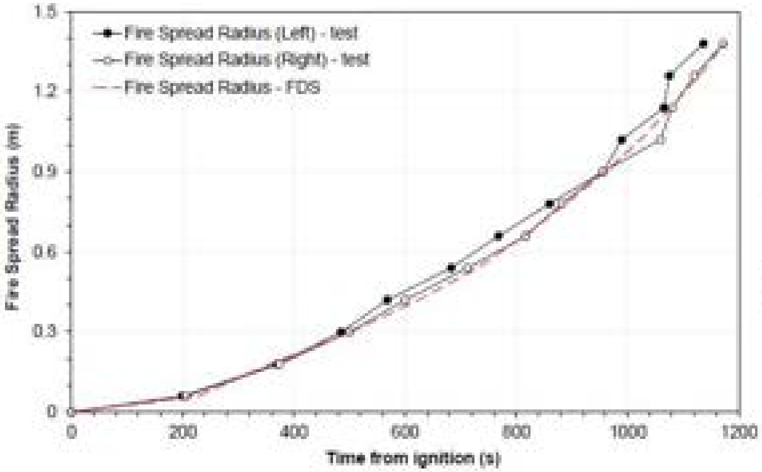
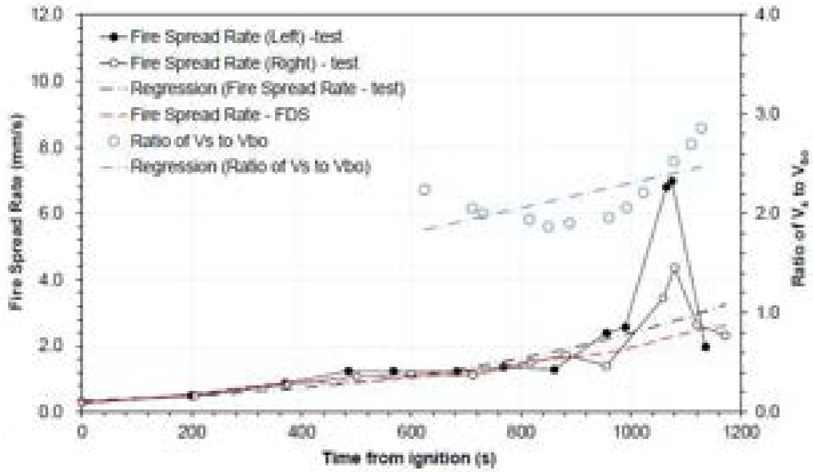
FDS modelling for calibration, “Liege test series”, LB7



Comparisons of the fire spread on top layer of wood cribs in FDS and LB7 test



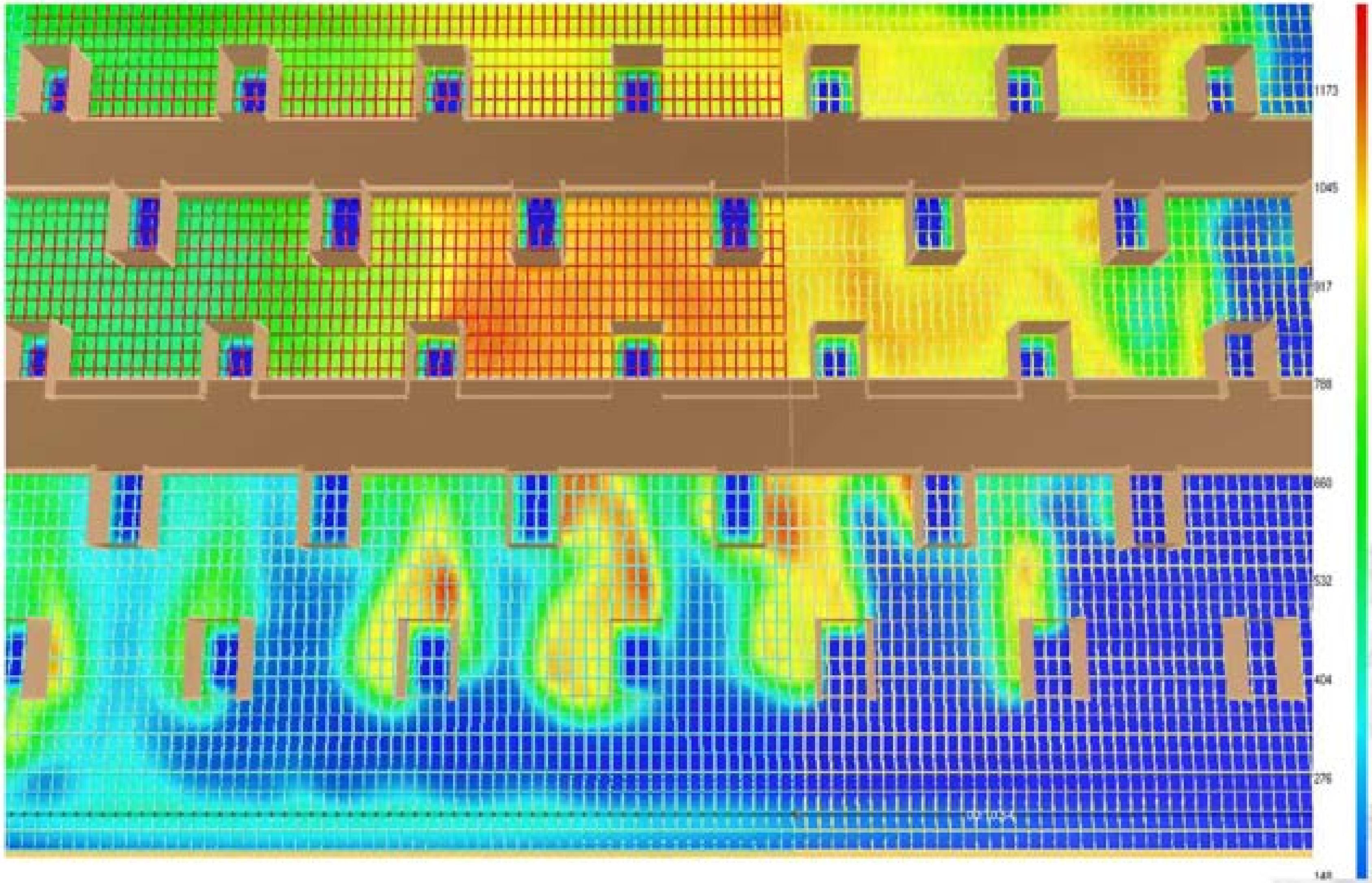
(a)



(b)

Comparisons between the FDS model and test: (a) evolution of the fire spread radius for the top layer of cribs; (b) calculated fire spread rate for the top layer of cribs

FDS grid sensitivity studies, "Liege test series", LB7



Full scale experiments*


[Test1 exp] Nadjai et al (2022) Large scale fire test Fire Safety Journal 130 (2022) 103575.pdf - Adobe Acrobat Reader D...

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Fire Safety Journal 130 (2022) 103575

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Large scale fire test: The development of a travelling fire in open ventilation conditions and its influence on the surrounding steel structure

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Natural fire tests
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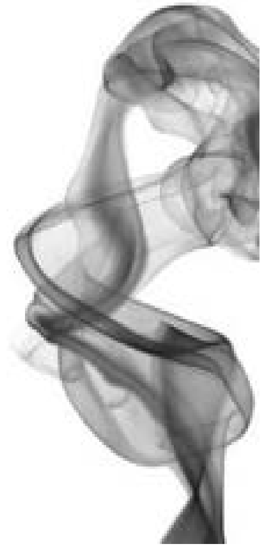
ABSTRACT

In the frame of the European RFCS-TRAFIR project, natural fire tests in large compartment were conducted by Ulster University, involving steel structure and aiming at understanding the conditions in which a travelling fire develops, how it behaves and impacts the surrounding structure. During the experimental programme, the path and geometry of the travelling fire was studied and temperatures, heat fluxes and spread rates were measured. The experimental data is presented in terms of gas temperatures recorded in the test compartment at different positions and levels. The influence of the travelling fire on the surround structure is presented in terms of the temperatures recorded in the selected steel columns and beams. The temperatures in the test compartment were dependent on the positioning of the travelling fire band as well as the height from the floor level. The non-uniform temperatures in the compartment lead to transient heating of the nearby structural steel elements, resulting in a reduction of their resistance which may influence the global structural stability. The results obtained will help to understand the behaviour of travelling fires and their influence on the structural members. This knowledge will help to reduce the travelling fire associated risks in future.

* Nadjai, A., Naveed, A., Charlier, M., Vassart, O., Welch, S., Glorieux, A. & Sjöström, J. (2022) "Large scale fire test: The development of a travelling fire in open ventilation conditions and its influence on the surrounding steel structure", Fire Safety J., 130:103575 doi:10.1016/j.firesaf.2022.103575



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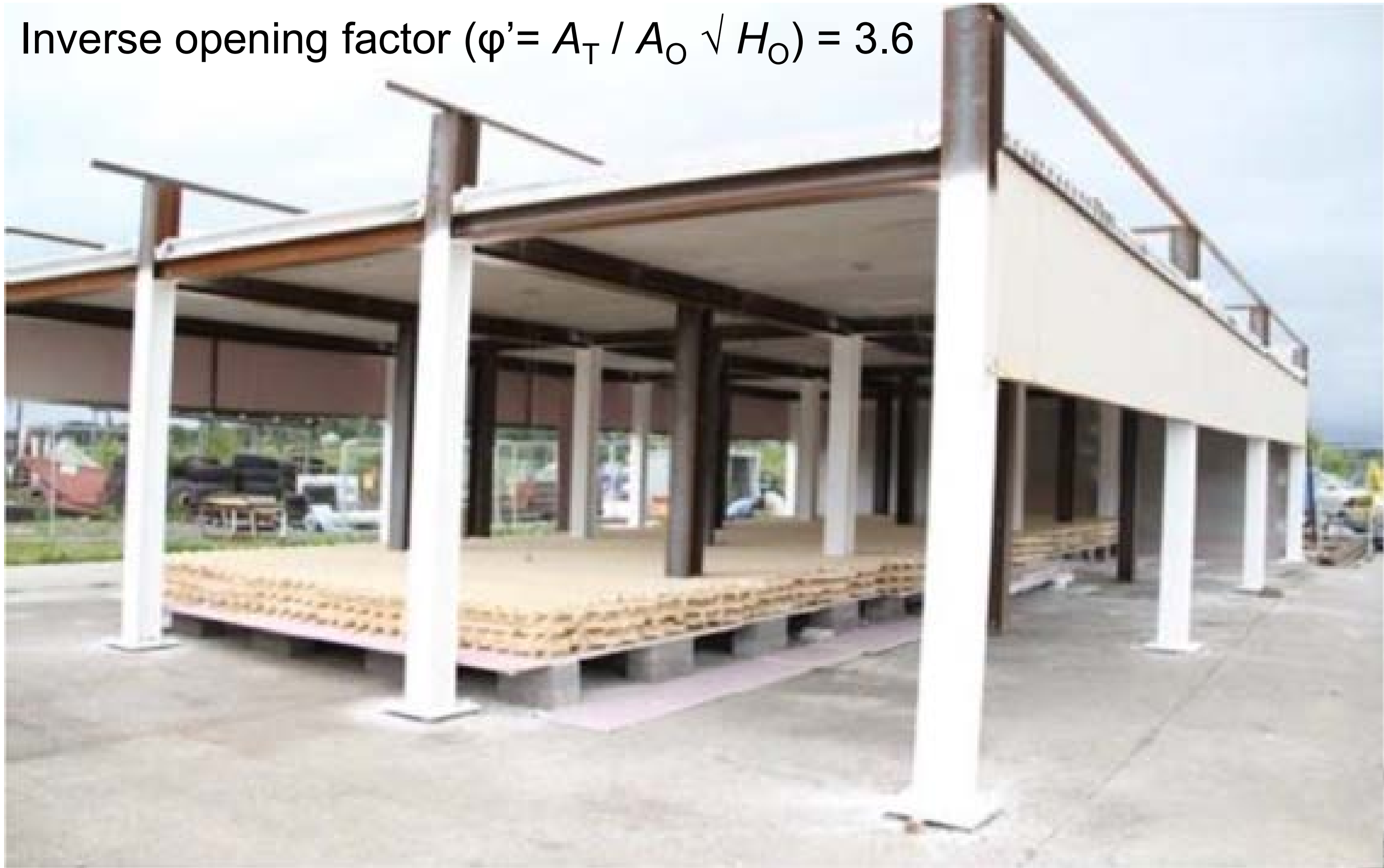
TRAFIR Ulster test 1

Inverse opening factor ($\varphi' = A_T / A_O \sqrt{H_O}$) = 3.6



Nadjai, A., Naveed, A., Charlier, M., Vassart, O., Welch, S., Glorieux, A. & Sjöström, J. (2022) “Large scale fire test: The development of a travelling fire in open ventilation conditions and its influence on the surrounding steel structure”, Fire Safety J., 130:103575 doi:10.1016/j.firesaf.2022.103575

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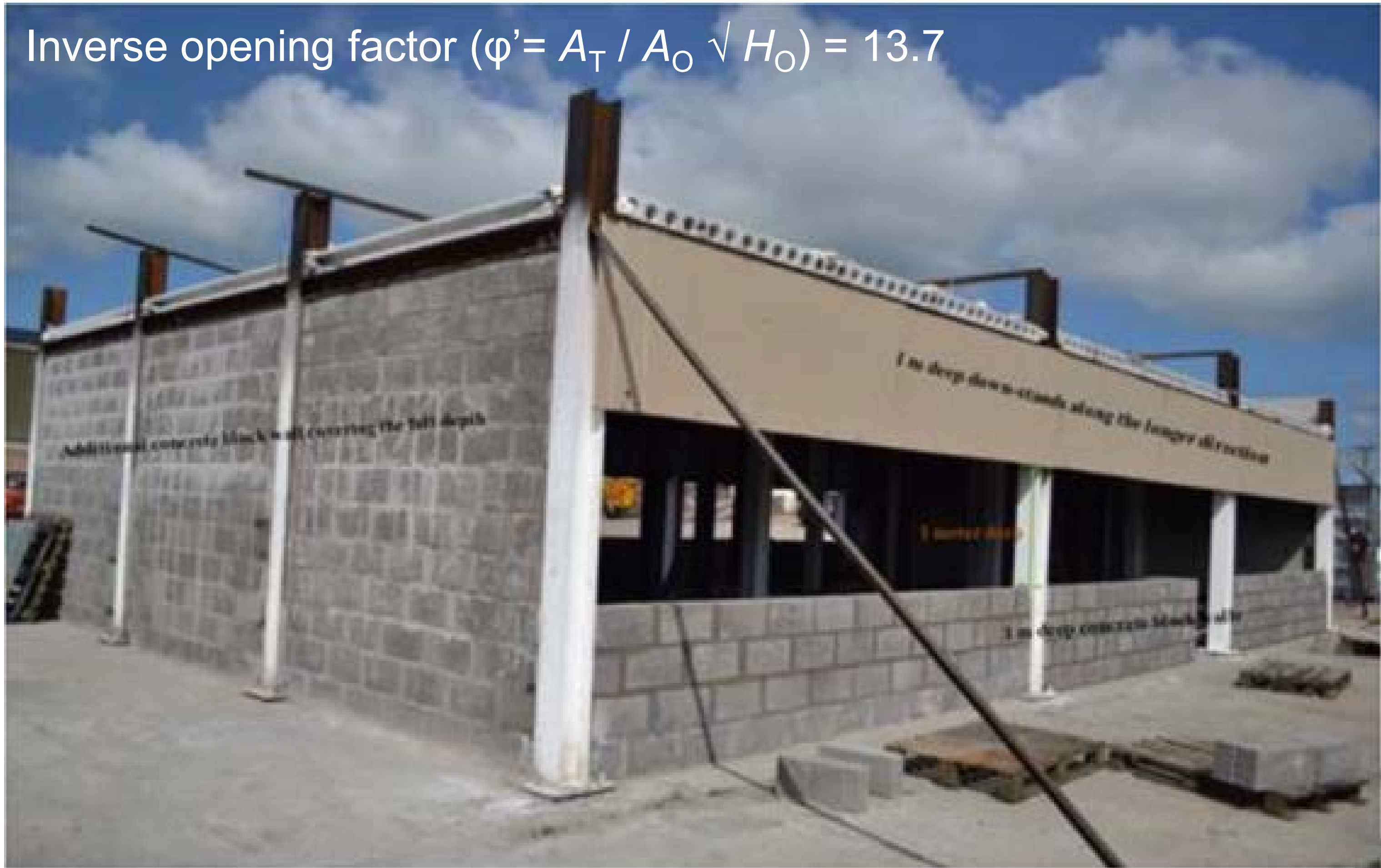
TRAFIR Ulster test 2

Inverse opening factor ($\varphi' = A_T / A_O \sqrt{H_O}$) = 13.7



TRAFIR Ulster test 3*

Inverse opening factor ($\varphi' = A_T / A_O \sqrt{H_O}$) = 41.7

Alam, A., Nadjai, A., Charlier, M., Vassart, O., Welch, S., Sjöström, J. & Dai, X. (2022) “Large scale travelling fire tests with open ventilation conditions and their effect on the surrounding steel structure– The second fire test”, J. Constr. Steel Res. 107032 doi:10.1016/j.jcsr.2021.107032

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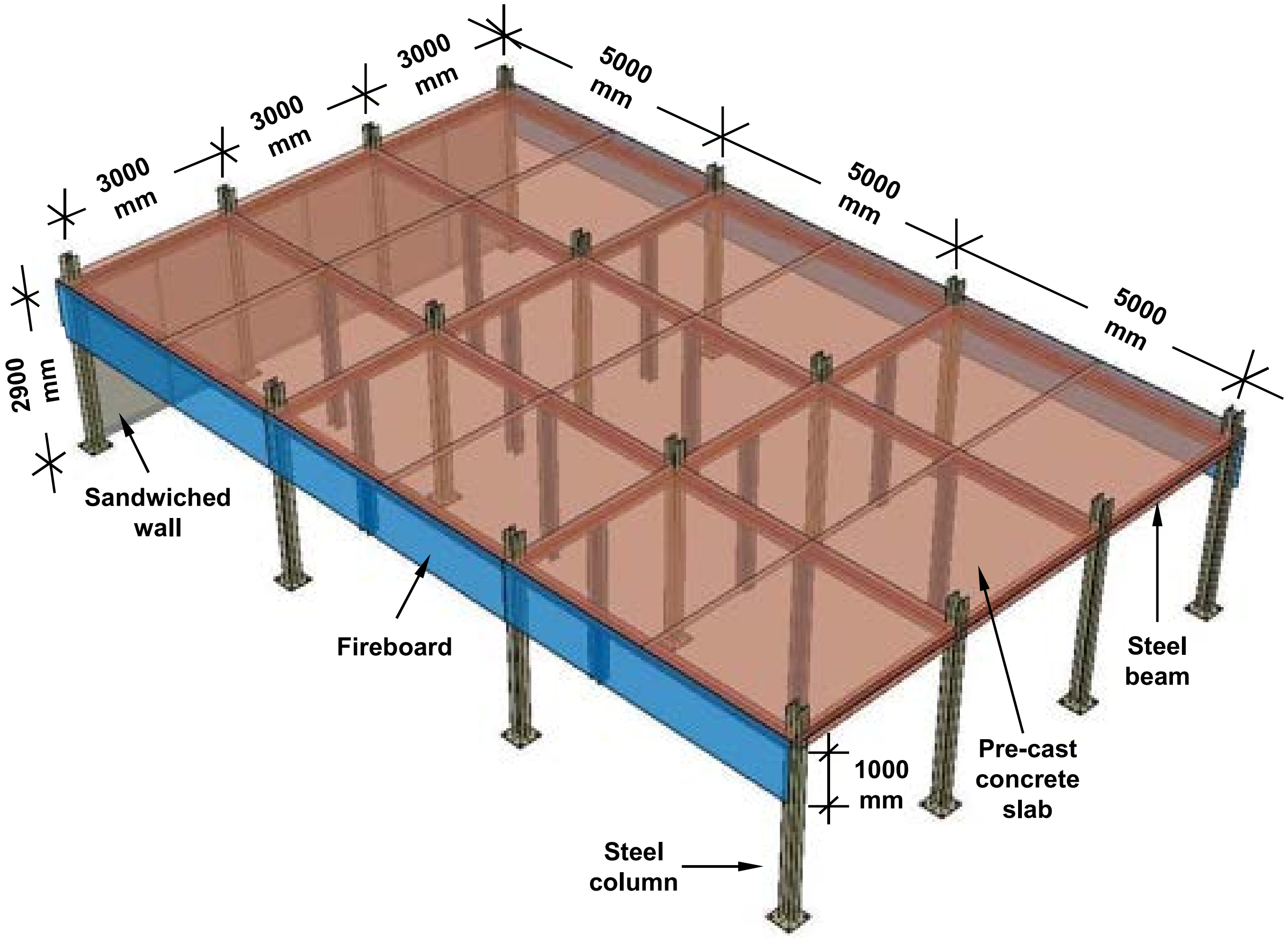
TRAFIR Ulster Travelling Fire Test 1

- Test compartment in 3D view:



TRAFIR Ulster Travelling Fire Test 1, compartment in 3D view

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TRAFIR Ulster Travelling Fire Test 1

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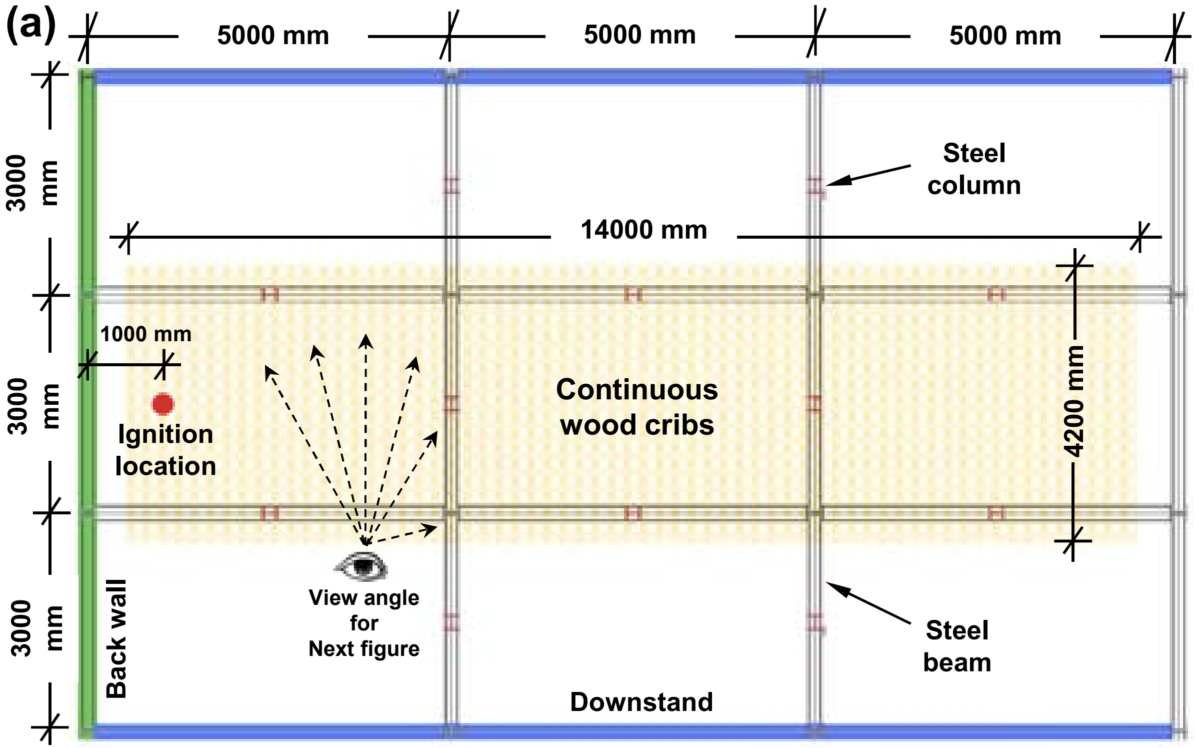
Nadjai, A., Naveed, A., Charlier, M., Vassart, O., Welch, S., Glorieux, A. & Sjöström, J. (2022) “Large scale fire test: The development of a travelling fire in open ventilation conditions and its influence on the surrounding steel structure”, Fire Safety J., 130:103575 doi:10.1016/j.firesaf.2022.103575

TRAFIR Ulster Travelling Fire Test 1

- **Wood sticks arrangement:**



Wood sticks arrangement, (a) Layout in the compartment.

TRAFIR Ulster Travelling Fire Test 1

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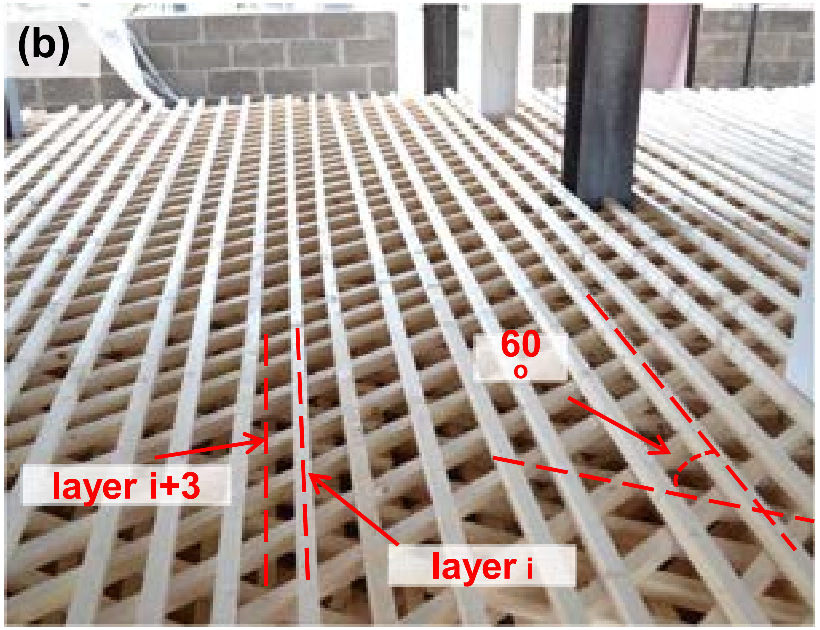
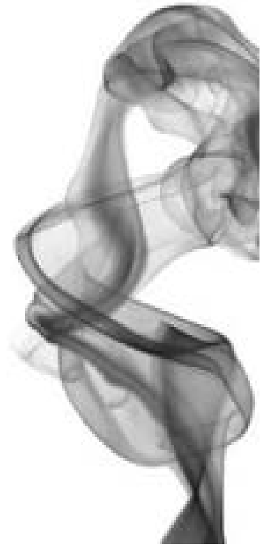
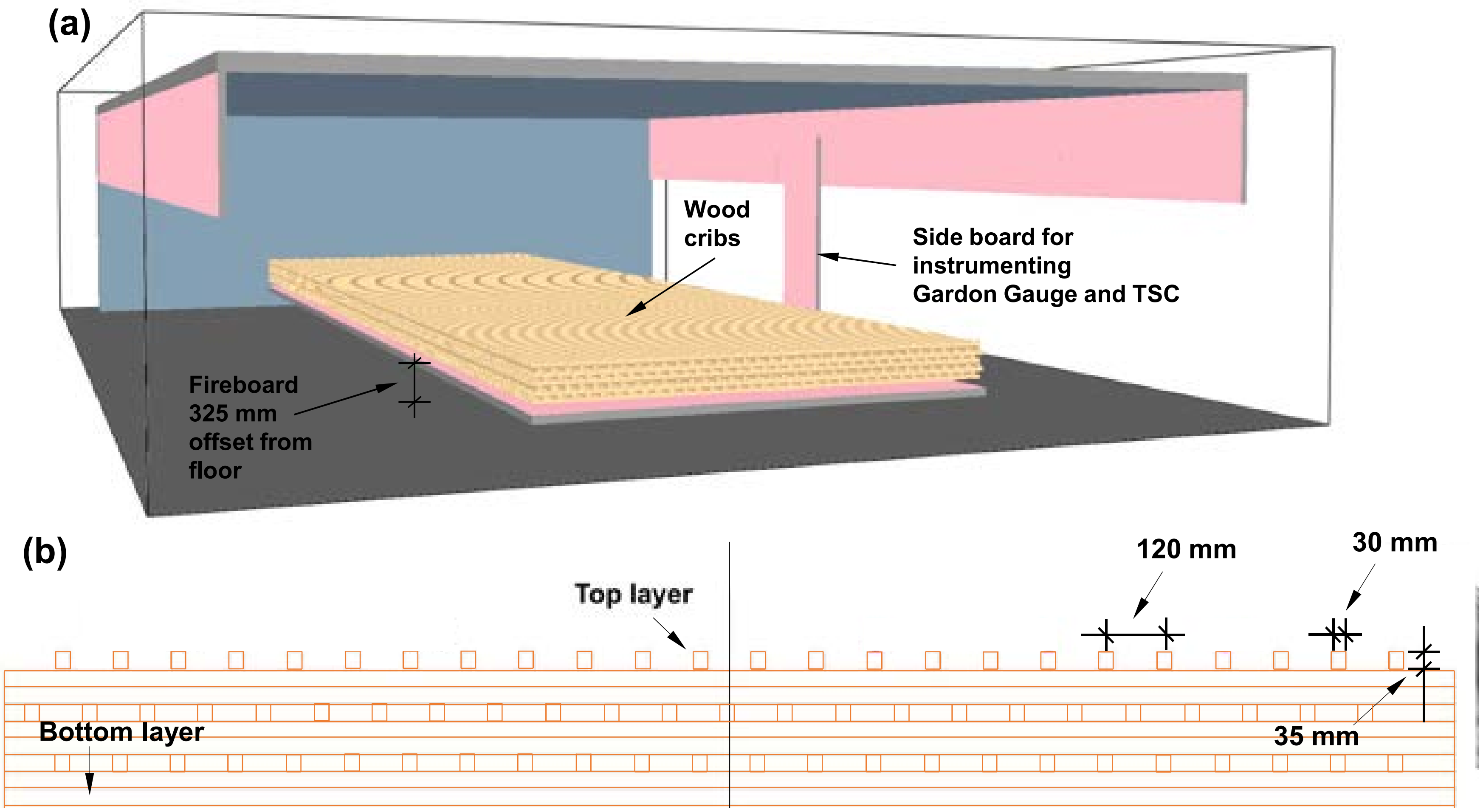
- Crib structure



Wood sticks arrangement, (b) Wood sticks orientation shifted 60° every layer, and for every three layers shifted horizontally for half of the wood stick pitch, same arrangement as the LB7 test from Gamba et al. [xx].



“Scaled-up” CFD Model – TRAFIR Ulster test 1



“Scaled-up” CFD model, (a) Skewed view, and (b) Representation of the wood sticks in side-elevation view.

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“Scaled-up” CFD Model – TRAFIR Ulster test 1

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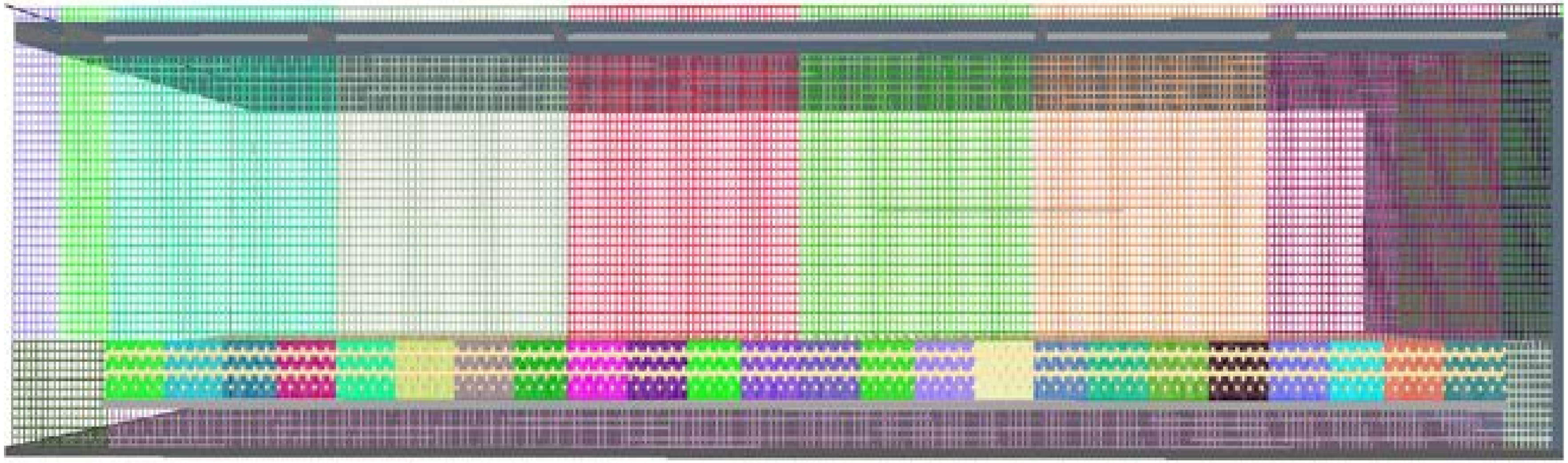
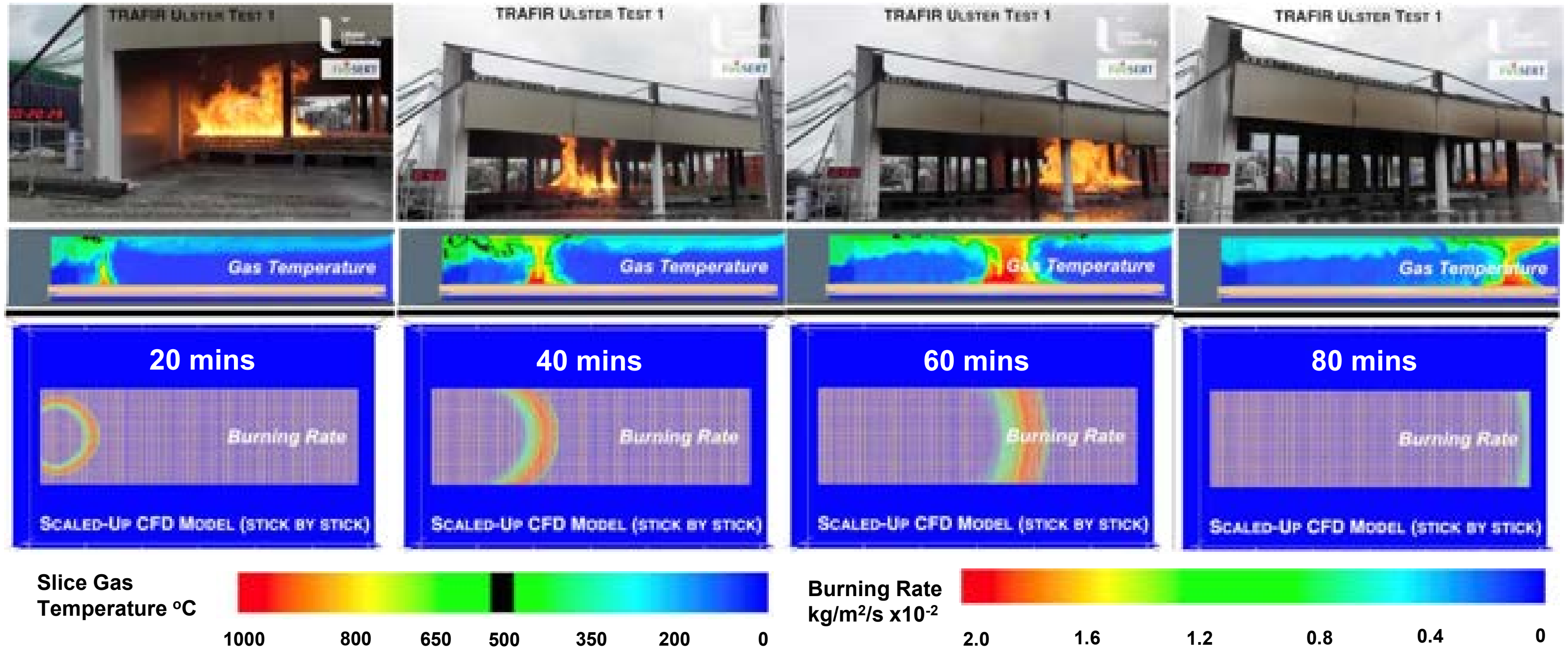
- Grid cell resolution in elevation view



Grid cell resolution of the model: 15 × 15 × 17.5 mm per cell for the wood sticks at solid phase, 60 × 60 × 70 mm and 30 × 30 × 35 mm cell size at the gas phase, total no. cells ~8.3 million, with 125 meshes.

Model Prediction vs. Test Results

- **Fire development comparison**



Scaled-up CFD model predicted fire spread comparison with the test, at 20, 40, 60 and 80 mins

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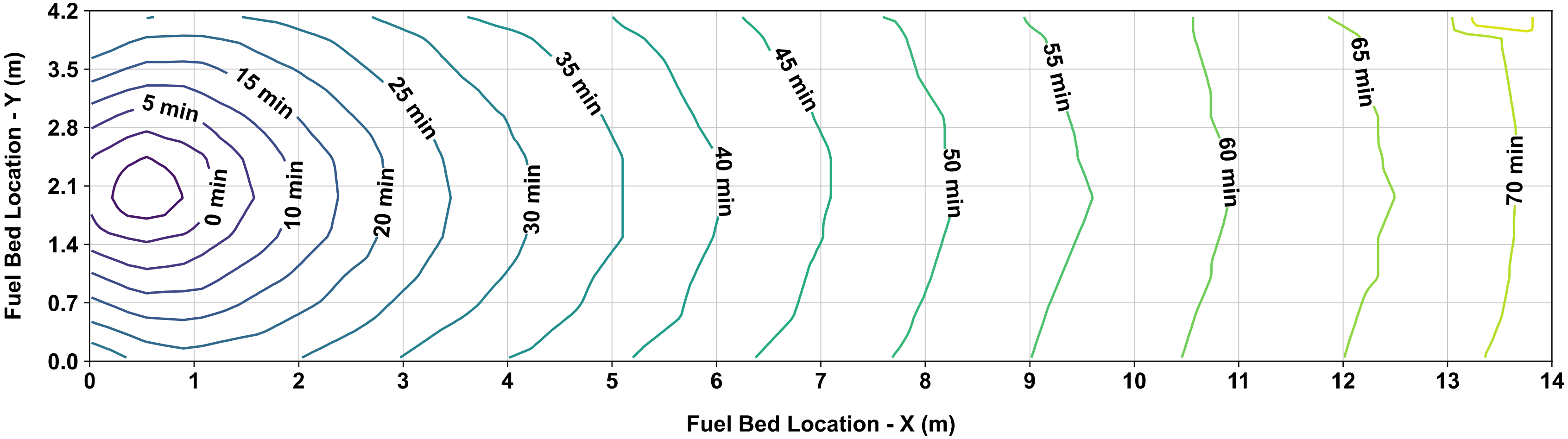
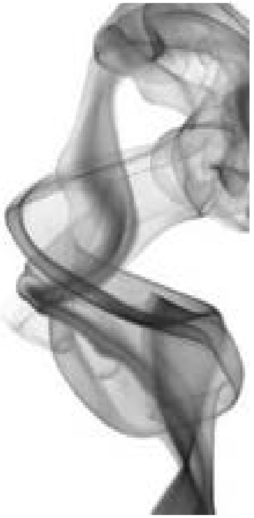
Further Understanding on Test via Model in-depth Characterisation

- **Fire Spread Contour**



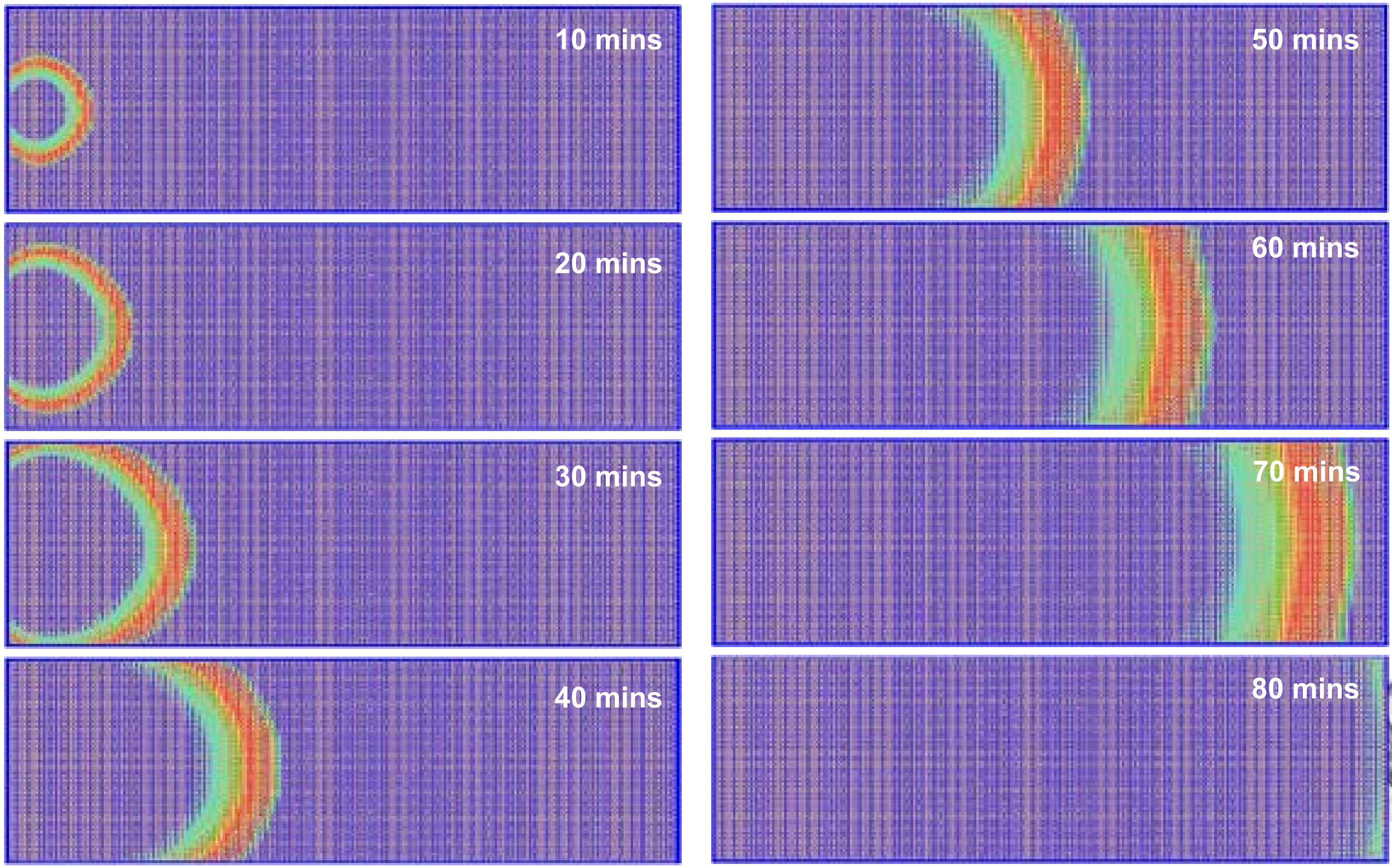
Fire spread development with 5 mins intervals, interpreted from the model



Further Understanding on Test via Model in-depth Characterisation

- ## Fire Spread Contour

Burning Rate
kg/m²/s x10^{-2}
2.0 1.6 1.2 0.8 0.4 0



Burning rate of the continuous fuel bed with 10 mins intervals

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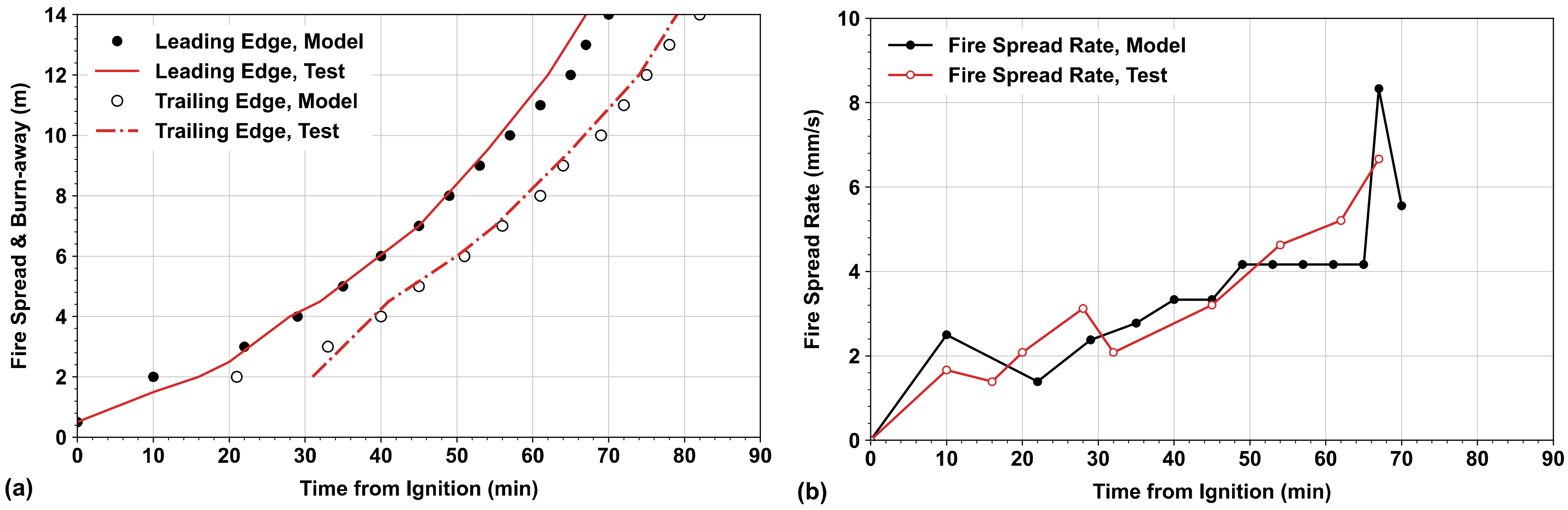
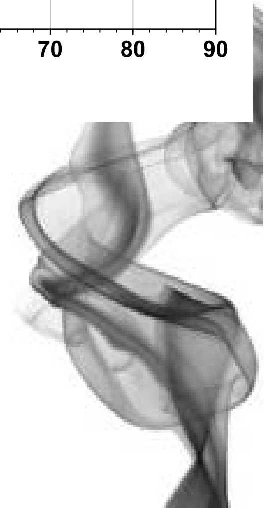
Model Prediction vs. Test Results

- Fire spread & burn-away comparison

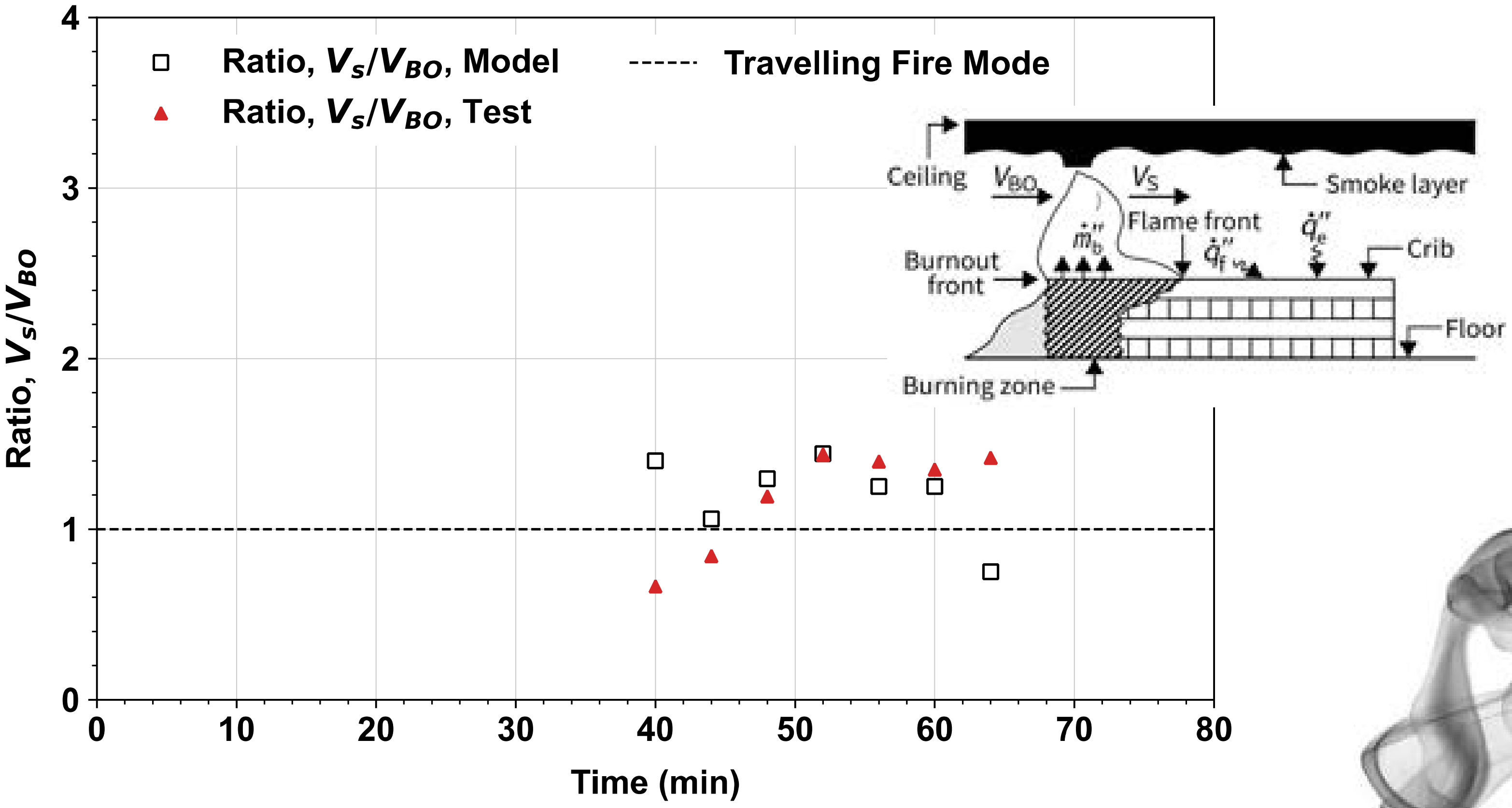


Comparison between the test and the model at compartment centreline along fire trajectory, (a) Fire spread distance & burn-away, and (b) Fire spread rate.

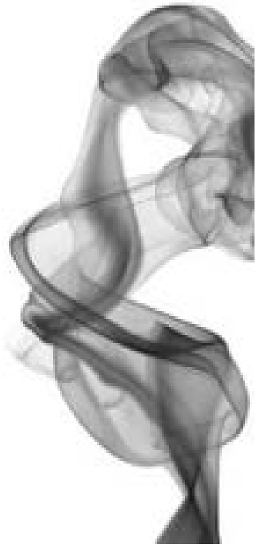


Model Prediction vs. Test Results

- Fire mode comparison



Comparison on fire mode parameter, V_S/V_{BO}: velocity of the flame spread front to velocity of the flame burnout front.



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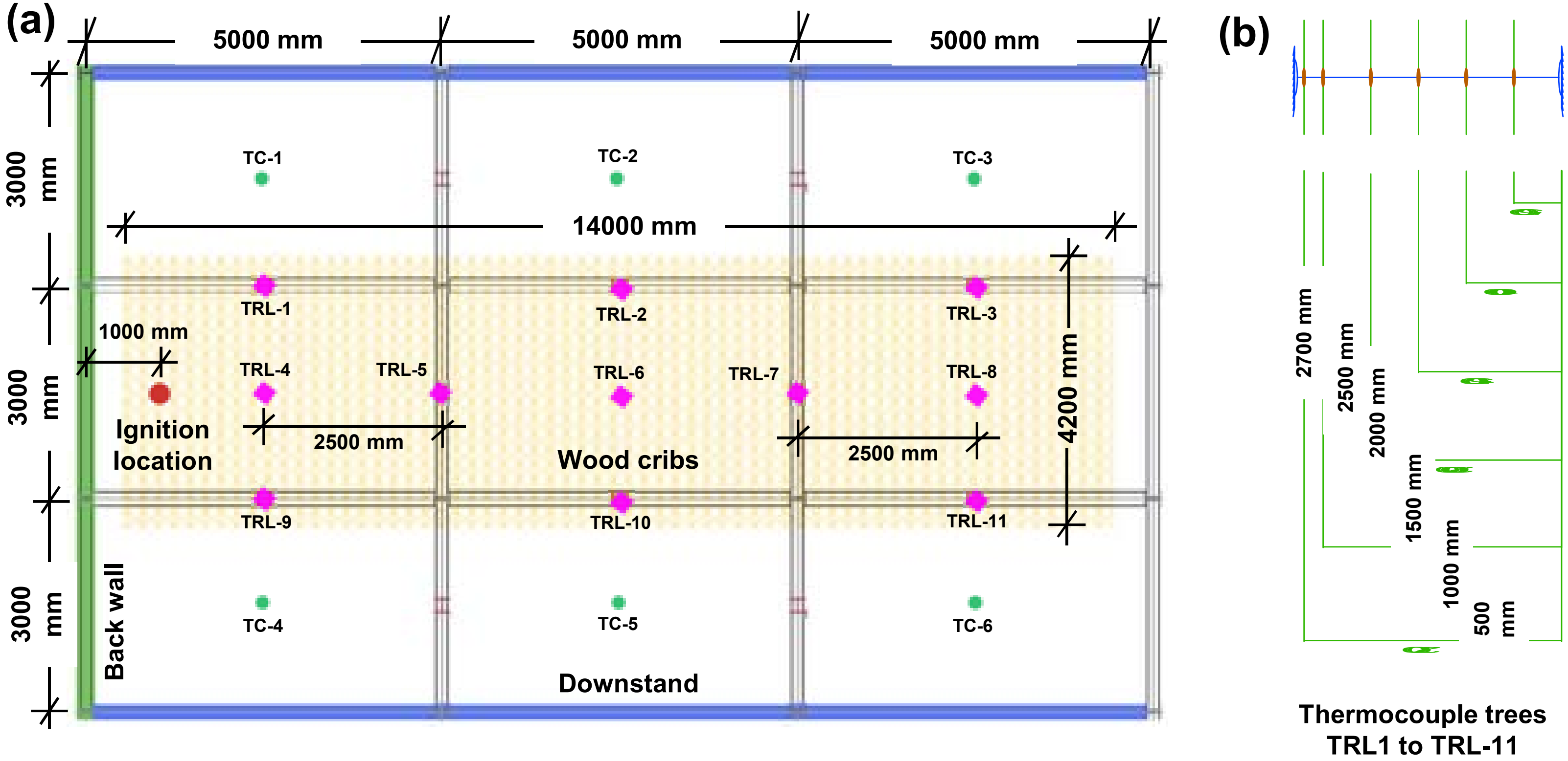
Model Prediction vs. Thermocouple Test Results

- Thermocouple Temperatures



Location of the thermocouples for measuring gas phase temperatures, (a) plan view, TC-1 to TC-6 were thermocouples 200 mm below ceiling, (b) elevation view, TRL-1 to TRL-11 were thermocouple trees above the wood cribs.

Model Prediction vs. Test Results

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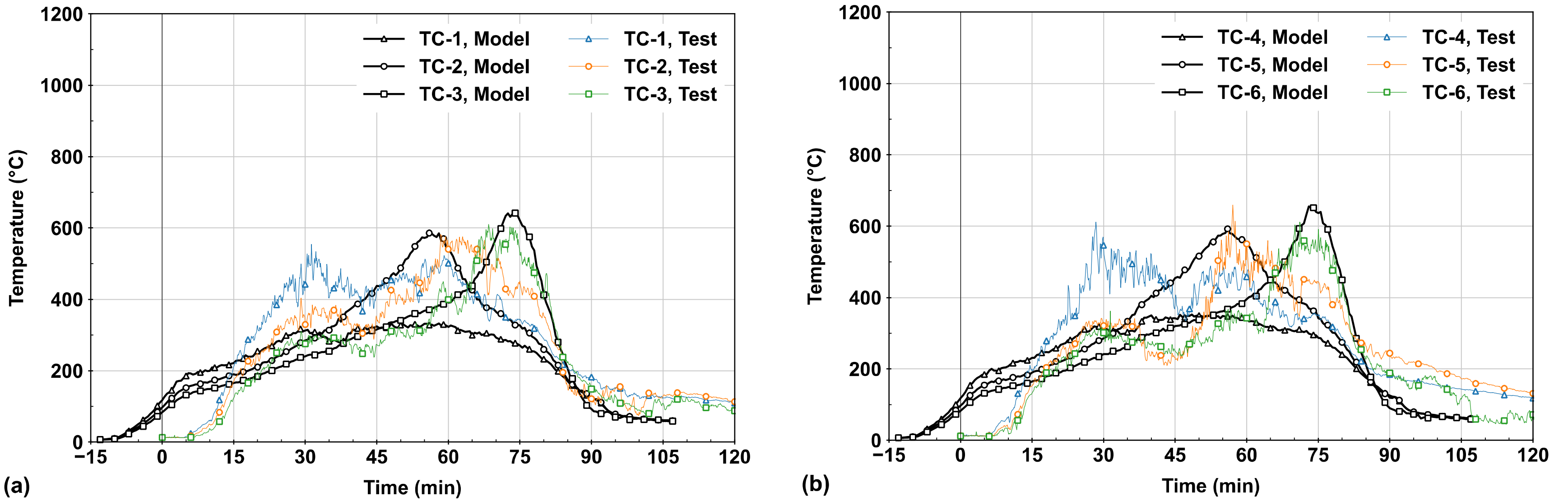
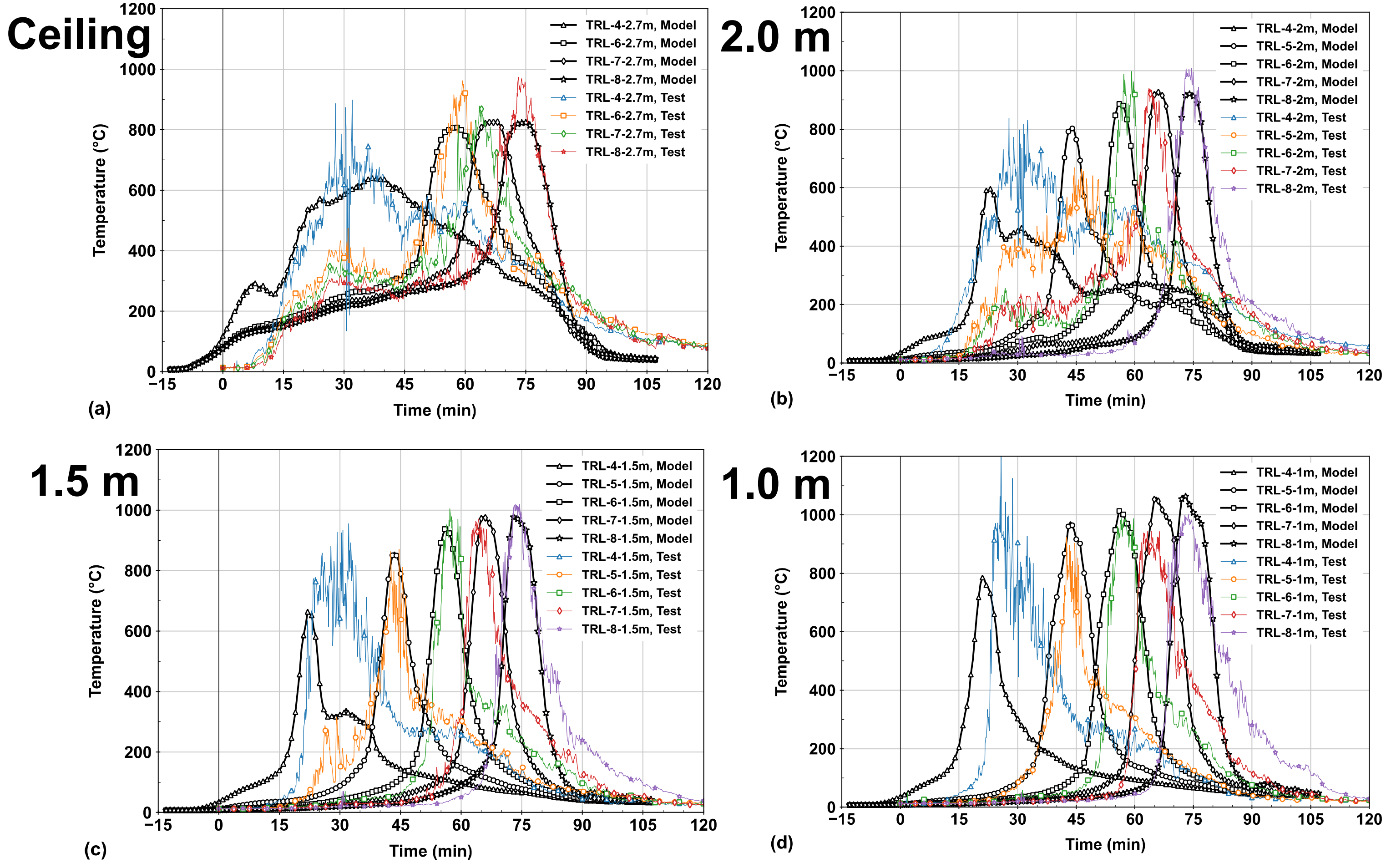
- Gas Phase Temperatures – symmetry near ceiling

Left external bays **Right external bays**



Comparison of the thermocouple temperatures, 200 mm from the ceiling level at side bays, (a) TC-1 to TC-3, and (b) TC-4 to TC-6.

Model Prediction vs. Test Results



Comparison of thermocouple temperatures at compartment centreline along fire trajectory, TRL-4 to TRL-8, (a) ceiling level (note: TRL-5-2.7m failed during test data acquisition), (b) 2 m from floor level, (c) 1.5 m from the floor level, and (d) 1 m from the floor level (i.e., 0.265 m from the fuel bed top level).

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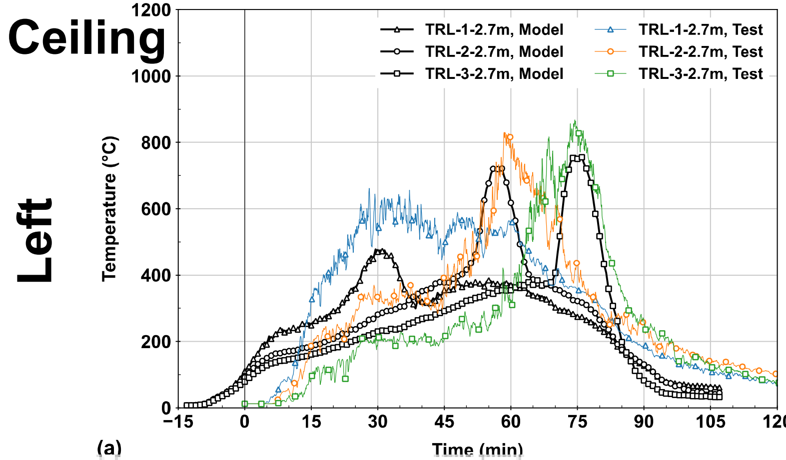
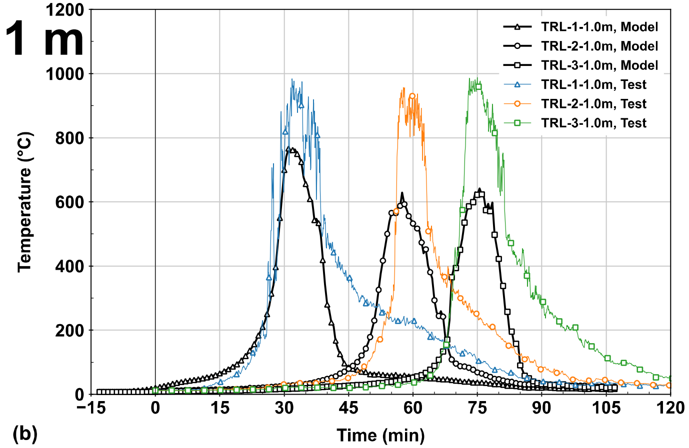
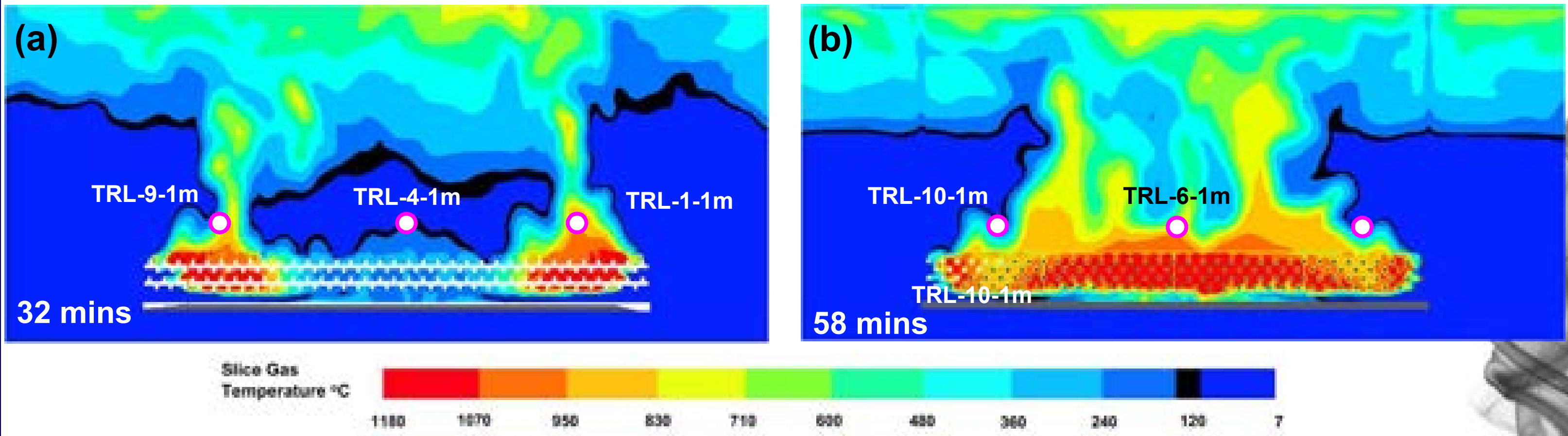
Model Prediction vs. Test Results





Comparison of thermocouple temperatures along fire trajectory and longitudinal fuel bed edges, (a) TRL-1 to TRL-3 at ceiling level, (b) TRL-1 to TRL-3 at 1 m from floor level (i.e., 0.265 m from fuel bed top level)



Gas phase temperature contour of the compartment 'slice' at specific time, (a) TRL-1/4/9 'slice' at 32 mins, (b) TRL-2/6/10 'slice' at 58 mins.

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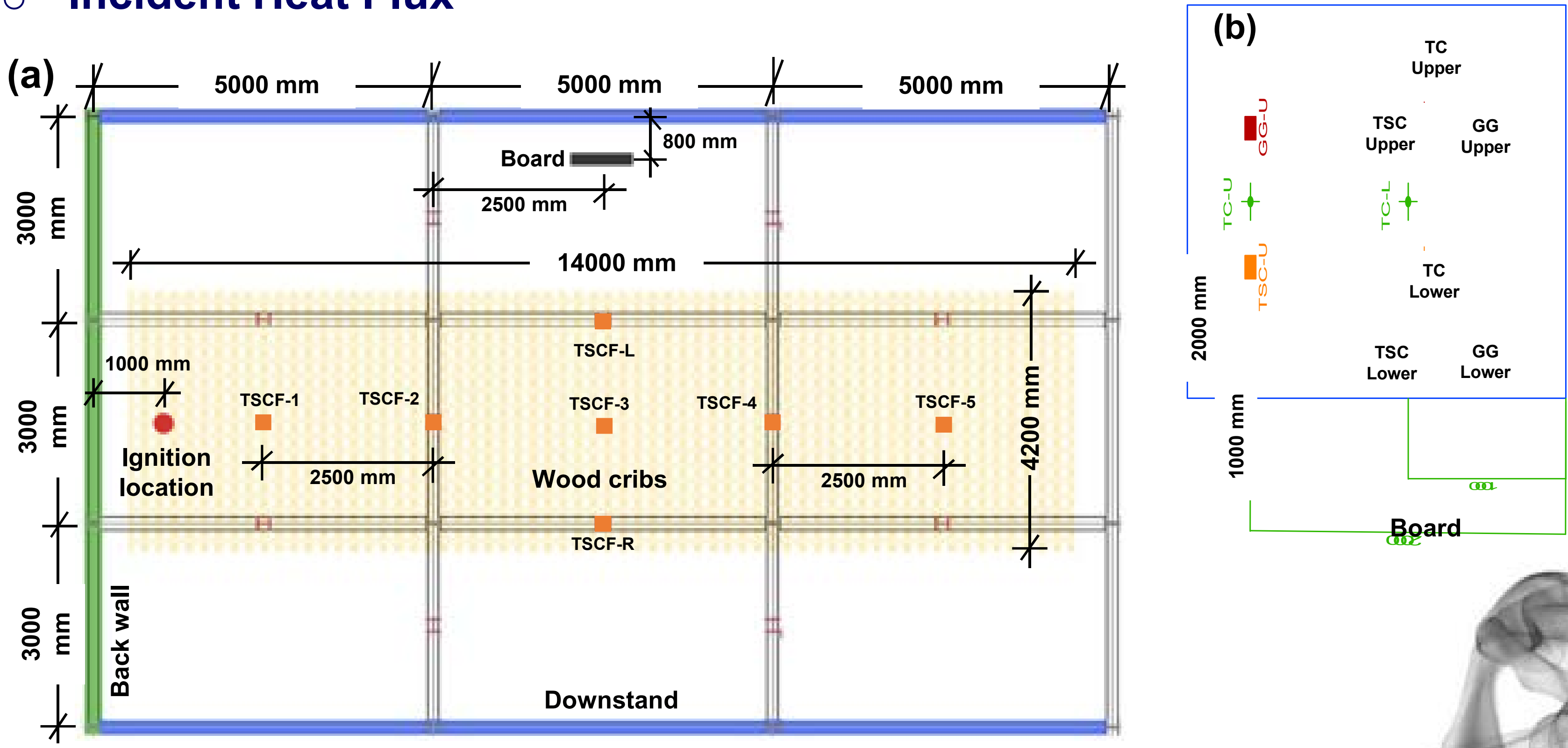
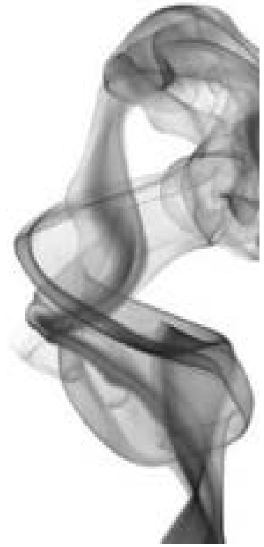
Heat flux instrumentation

- Incident Heat Flux

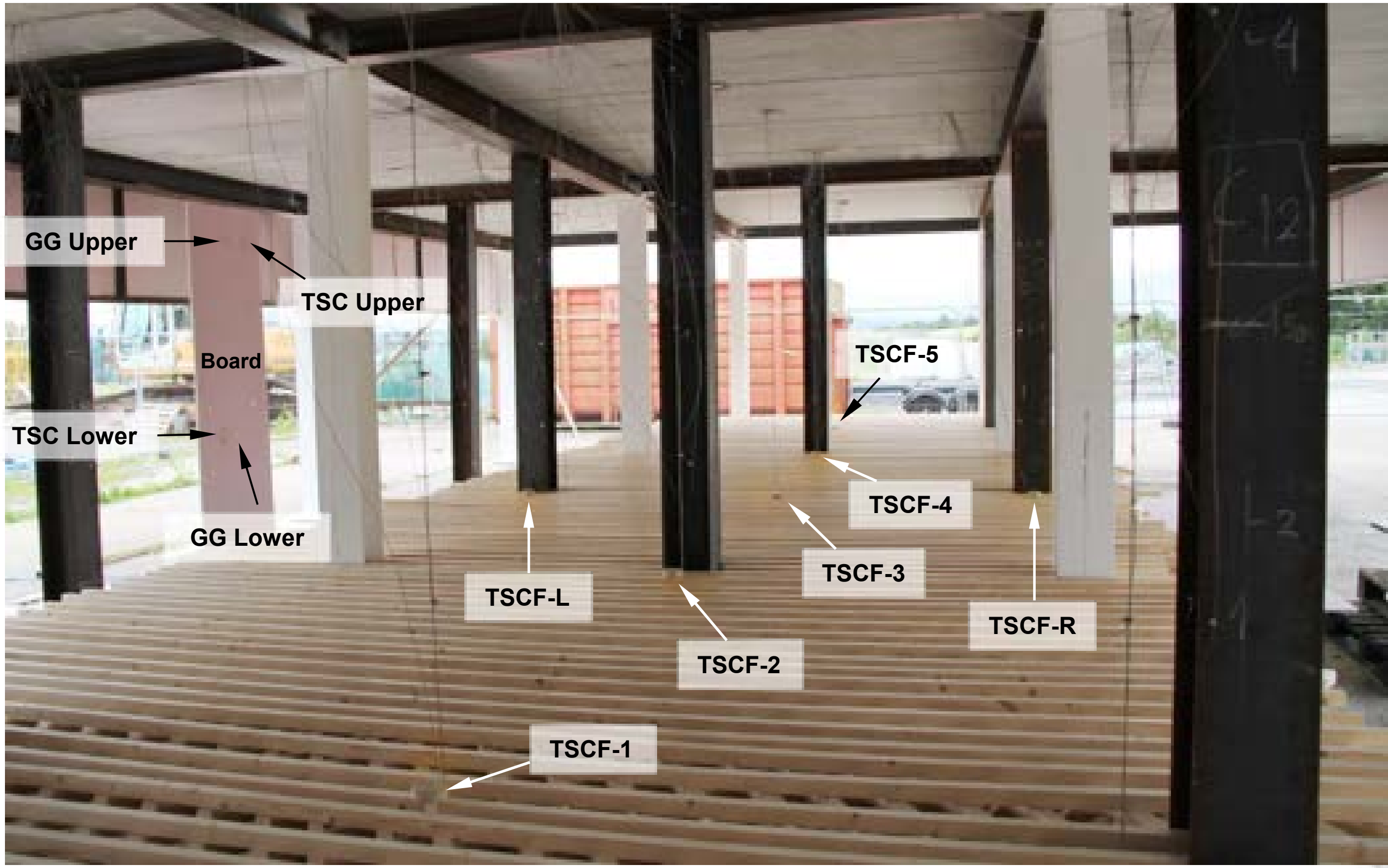


Location of the heat fluxes instrumentations, (a) plan view, TSCF-1 to TSCF-5 were thin skin calorimeters (TSC) on top of the fuel bed level, (b) board in elevation view, instrumented TSCs, Gordon Gauges (GG), and thermocouples (TC).



Heat flux instrumentation

- Incident Heat Flux



Location of the thin skin calorimeters (TSC) and Gordon Gauges (GG) inside of the compartment.

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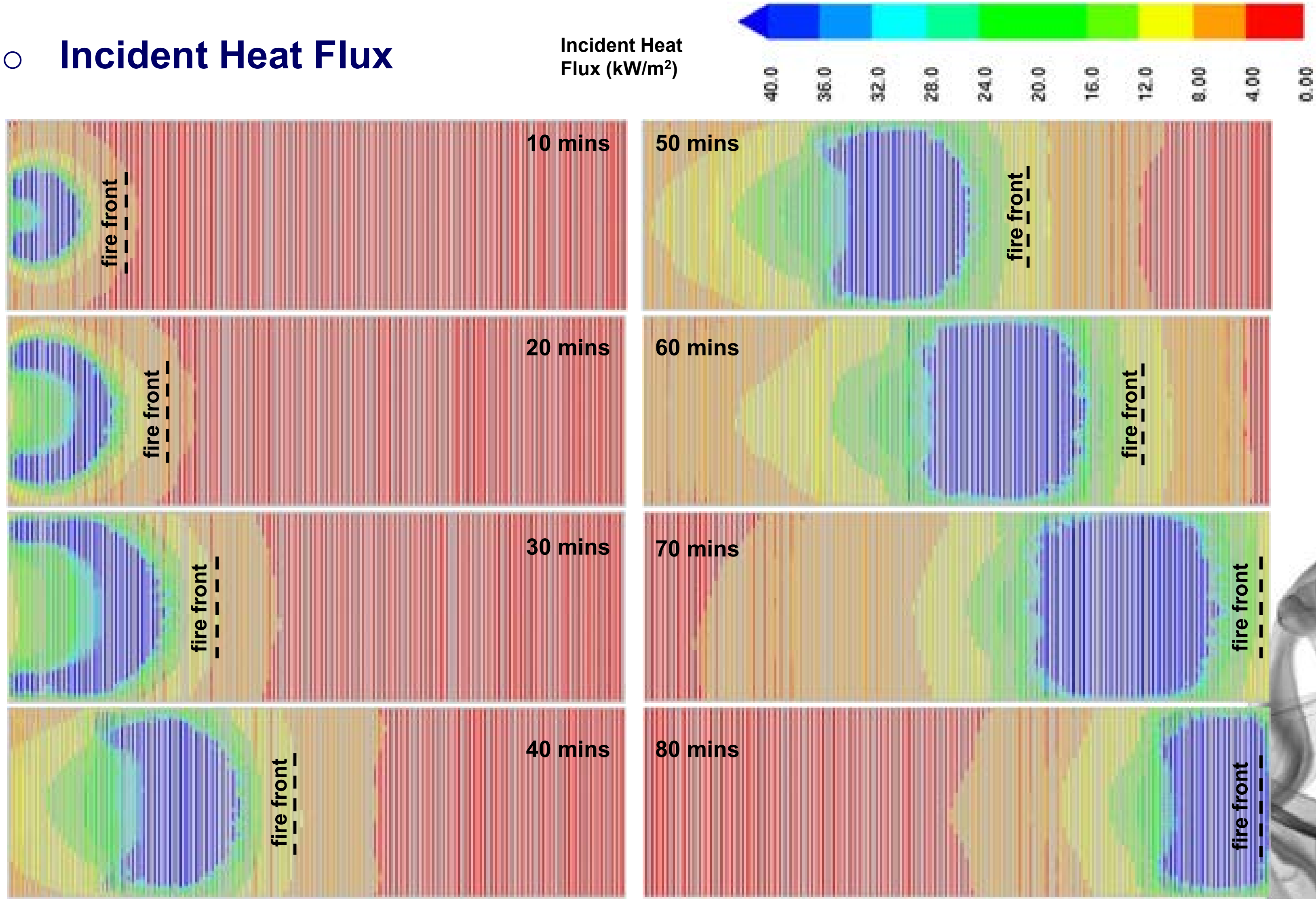
Heat flux analysis

- Incident Heat Flux



Incident heat flux on the top layer of wood sticks with 10 mins intervals

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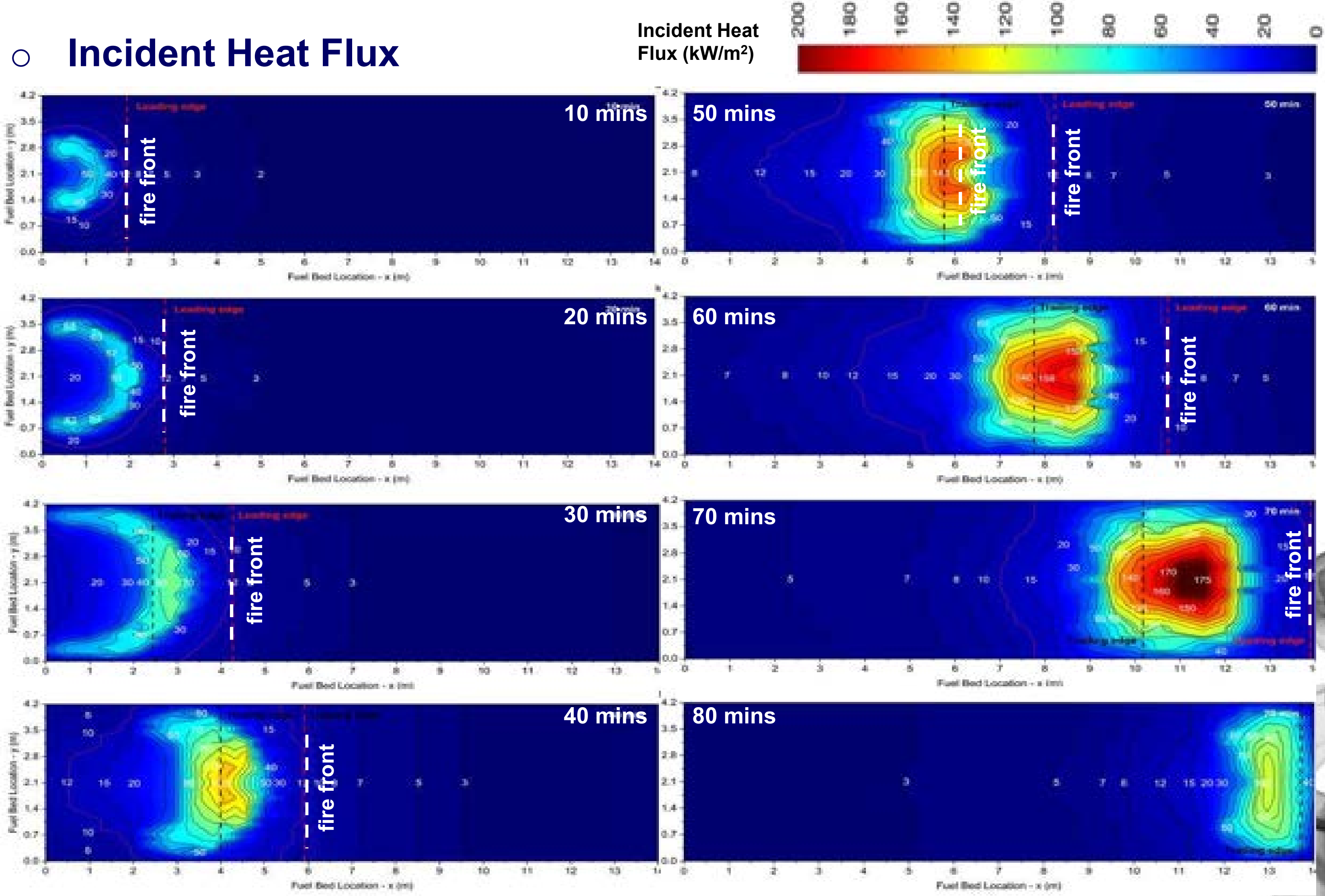
Heat flux analysis

- Incident Heat Flux



Incident heat flux on the top layer of wood sticks with 10 mins intervals

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Model Prediction vs. Test Results

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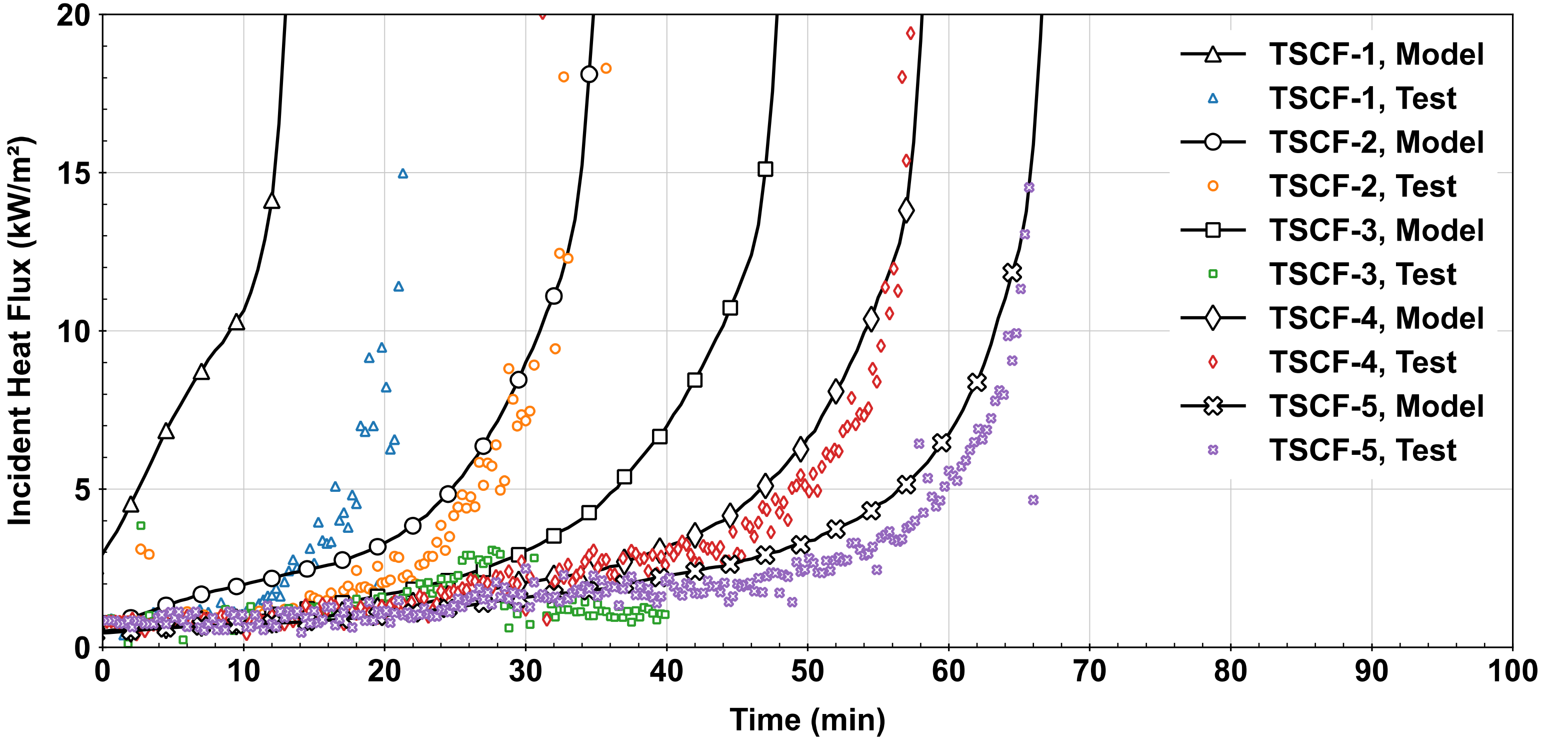
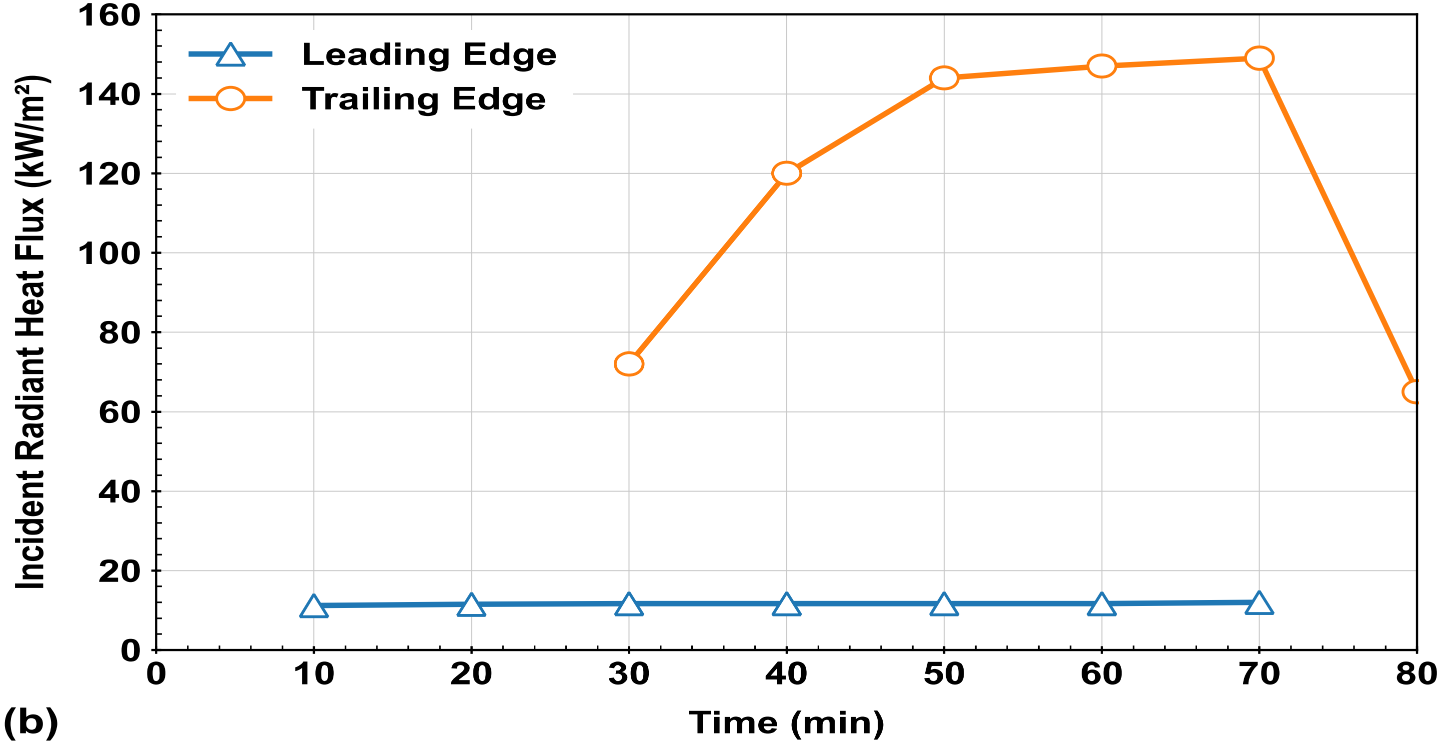
- Incident Heat Flux at TSC



Comparison on incident heat fluxes from thin skin calorimeters (TSC) at fuel bed top level centreline along fire trajectory (TSCF-3 failed during test data acquisition after 30 mins).

Heat flux analysis

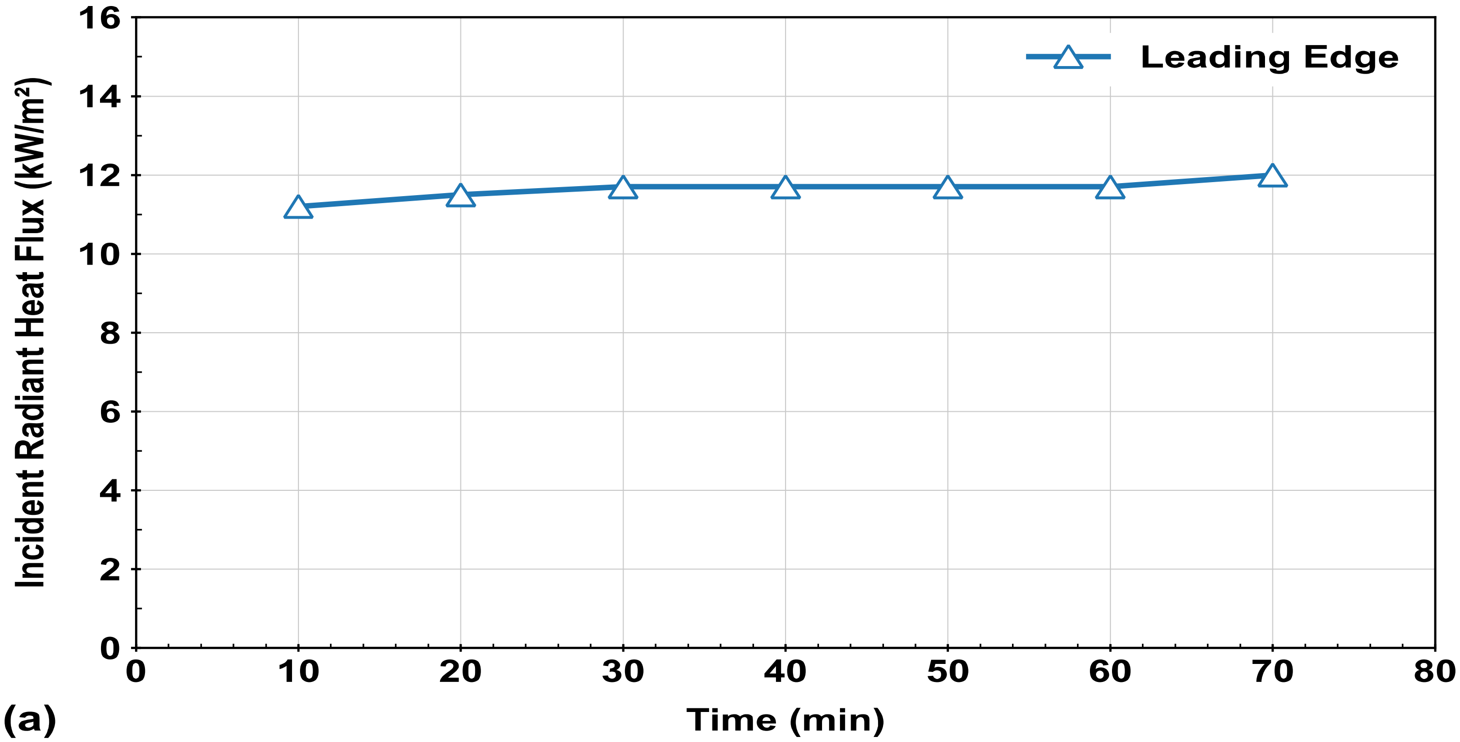
- Incident Heat Flux at ignition/burn-out from model



Comparison on incident heat fluxes from thin skin calorimeters (TSC) at fuel bed top level centreline along fire trajectory (TSCF-3 failed during test data acquisition after 30 mins).

Heat flux analysis

- Incident Heat Flux at ignition from model



Comparison on incident heat fluxes from thin skin calorimeters (TSC) at fuel bed top level centreline along fire trajectory (TSCF-3 failed during test data acquisition after 30 mins).

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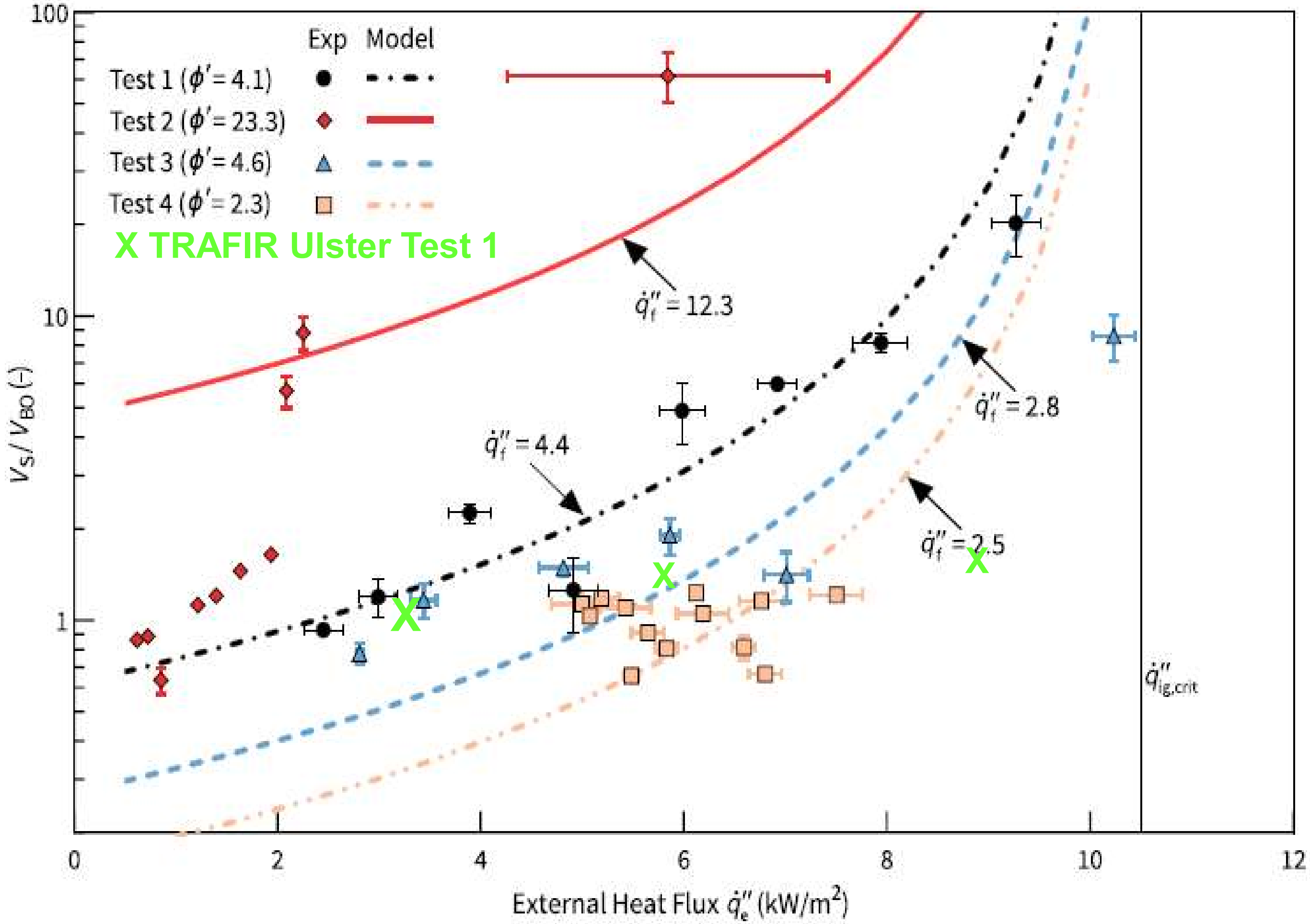
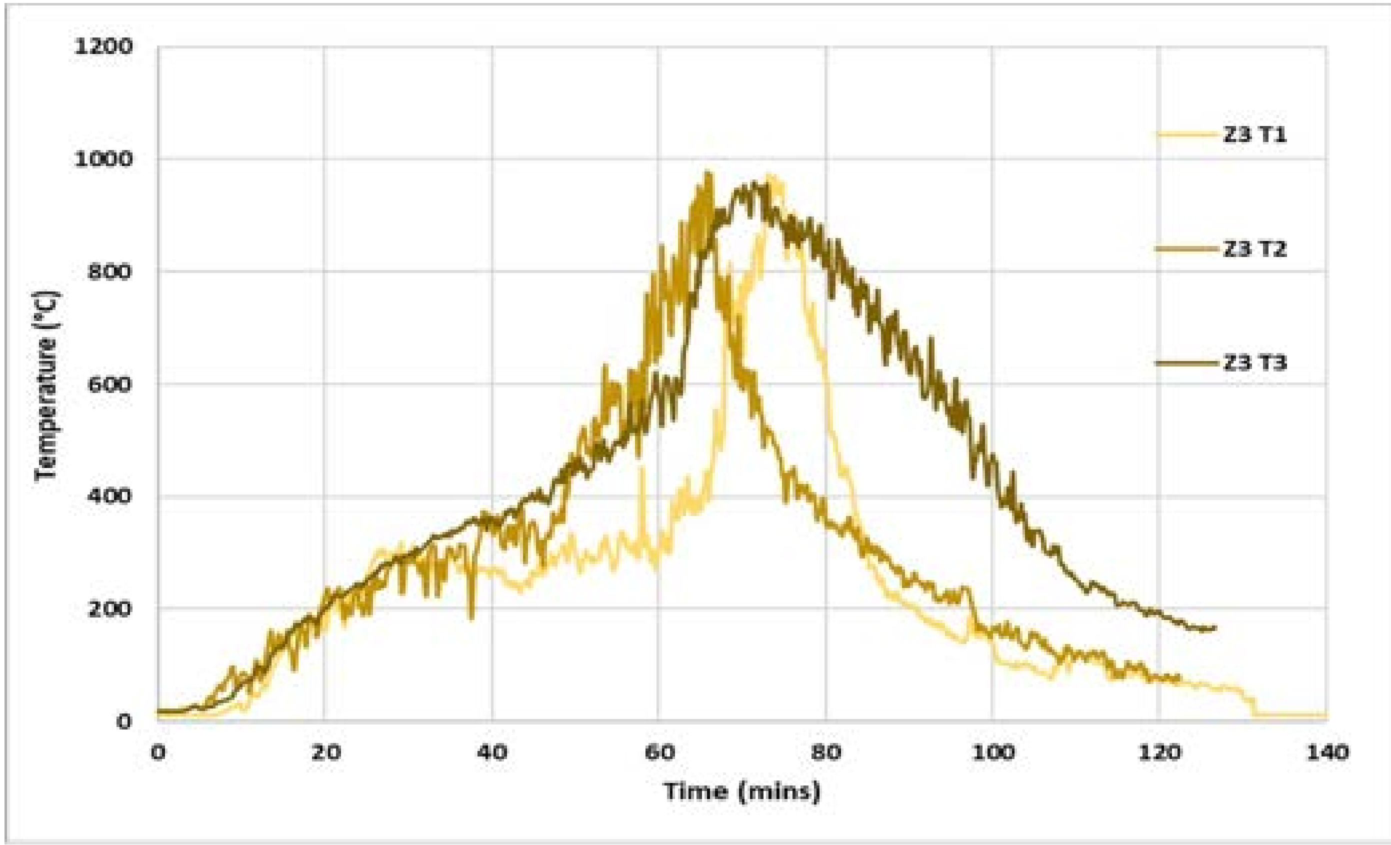
Phenomenological model v experiments

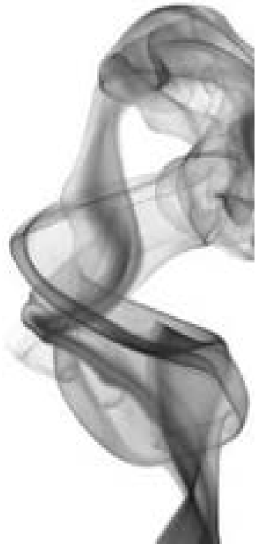


Gupta, V, Osorio, AF, Torero, JL, & Hidalgo, JP 2021, 'Mechanisms of flame spread and burnout in large enclosure fires', Proc. Comb. Inst. 38(3):4525–4533

Opening factor study – test comparison (bay 3, T1-3)



Temperature history at top of compartment in bay 3 (end), tests 1-3



Opening factor study – test comparison (bays 1-3, T1-3)

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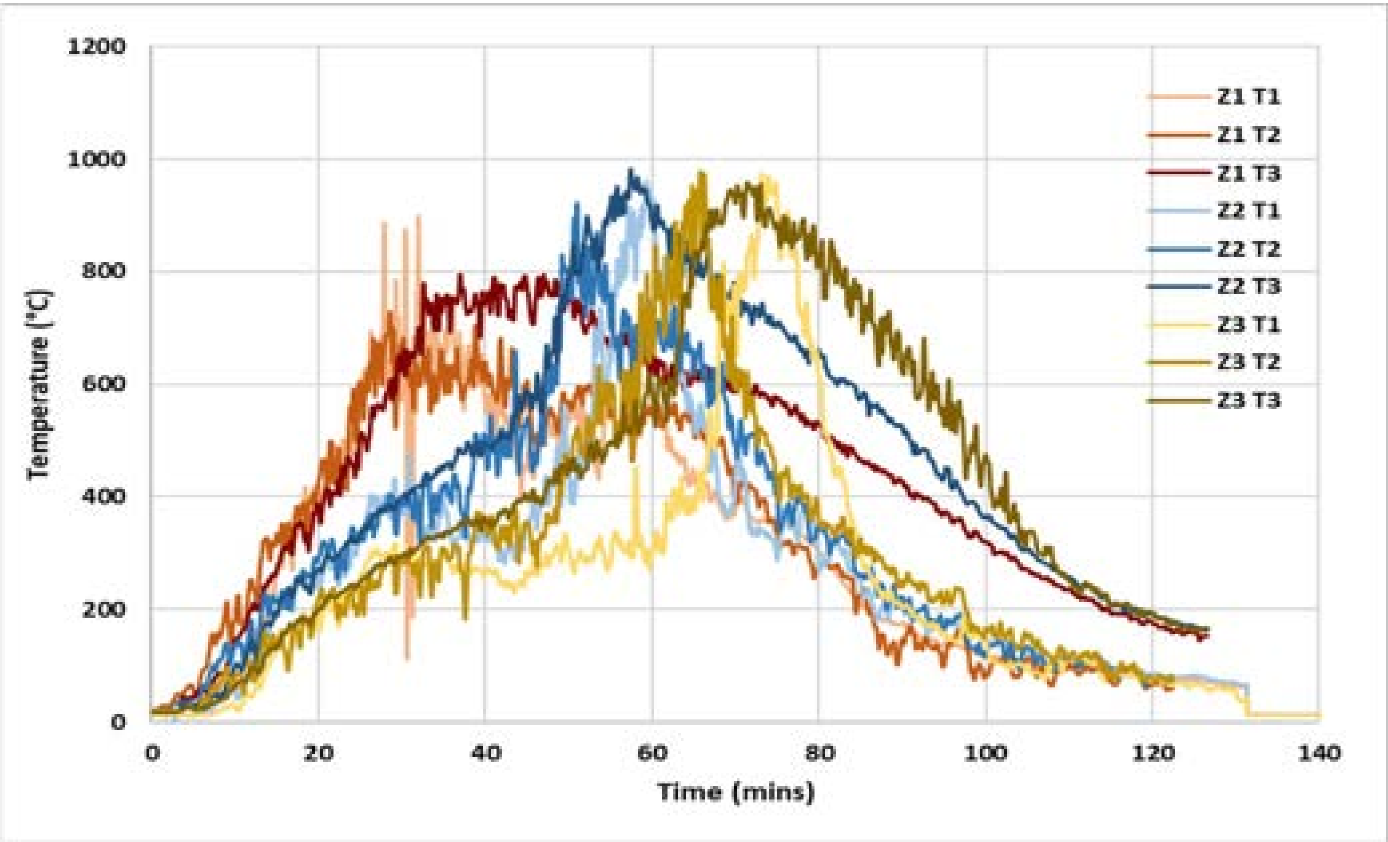
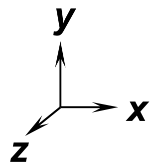


Temperature history at top of compartment in bays 1-3, tests 1-3

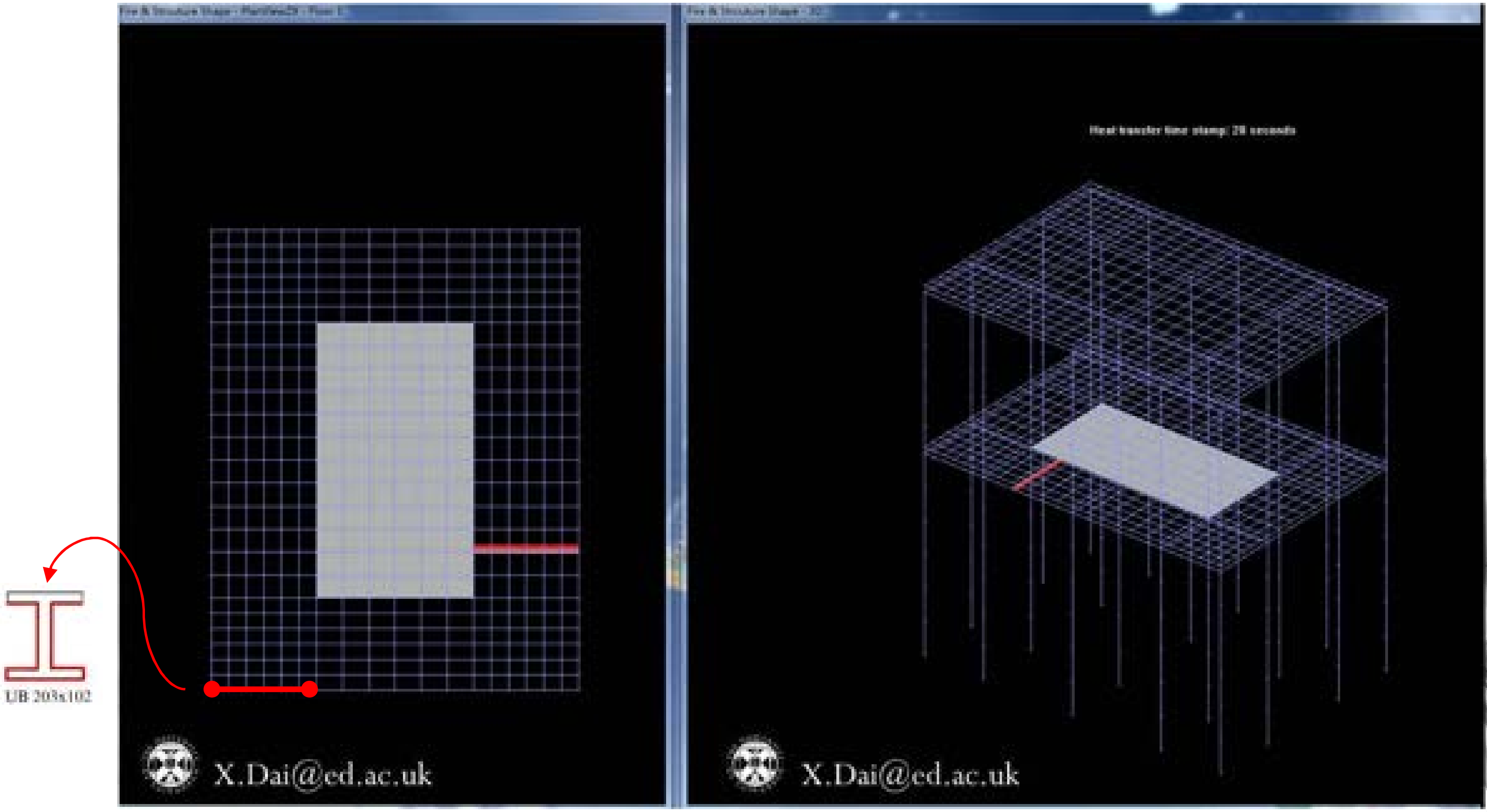
Extended travelling fire method

A steel-framed building with concrete slabs



Fire scenarios:

1. Fire starts on the **first floor**
2. Fire spread rate: **10 mm/s**
3. HRR per area: **500 KW/m²**
4. Fuel load density: **570 MJ/m²**



Visualization output of SIFBuilder during heat transfer analysis

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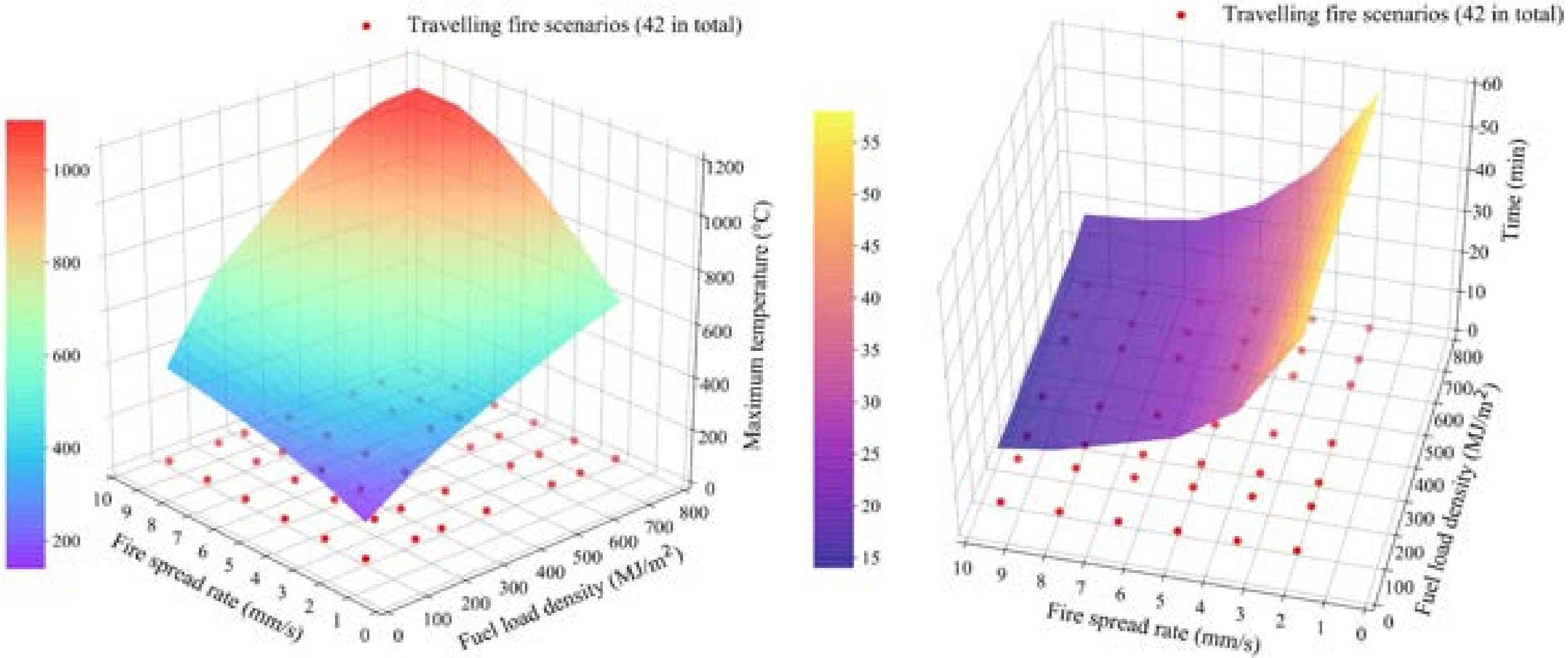
Parametric studies – ETFM for Veselí Test, fire spread rate & fuel load densities



Various combinations of different fire spread rates (ranging from 2 mm/s to 9.5 mm/s) and fuel load densities (ranging from 100 MJ/m² to 780 MJ/m²) with 42 travelling fire scenarios, marked with red dots as sampling points, with (a). maximum steel beam bottom flange temperatures at location 00; (b). time to reach the peak temperature of the steel beam bottom flange at location 00.

* Nan, Z., Dai, X., Chen, H., Welch, S. & Usmani, A. (2022) "A numerical investigation of 3D structural behavior for steel-composite structures under various travelling fire scenarios", Engineering Structures 247: 114587 doi:10.1016/j.engstruct.2022.114587

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Conclusions (1)

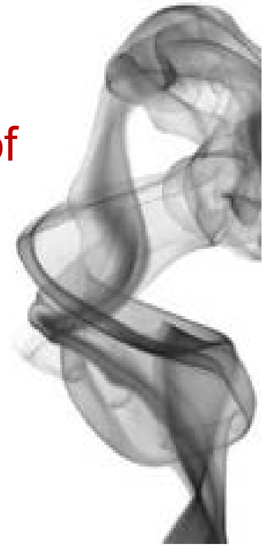
- Reconstruction of a uniform wood fuel bed for fire spread, is achieved through using a stick-to-stick model with simple pyrolysis and an ignition temperature setup. Compared with previous research the results show more parameters being comparable to the full suite of test data, suggesting potential credibility of the model for predicting fire spread rate, flame temperature, incidental radiant heat flux, burn away, and most importantly, the total HRR evolution.

- Previously observed discrepancies in the cooling phase temperatures are predominantly associated with limitations in representation of heat transfer processes associated with the glowing char; explicit treatment not currently included in FDS.

- The mesh scheme which adopts a finer mesh within the crib structure and relatively coarse mesh in the gas phase, provides a viable practical solution for modelling such crib fires, with potential for scaling up to compartment level. Some differences are found but they may be expected to be small when spread on upper surface of crib driven mainly by remote heating, not local flame front.

Conclusions (2)

- Results with a very fine mesh inside the crib structure (now 7.5/8.75mm cells, giving 12x4 cells between sticks in elevation) have confirmed the plausibility of the original results with a coarser mesh (15/17.5mm cells with 6x2 cells between sticks).
- The single crib baseline model has a total of 1.3M cells, simulation of 20 minutes test using 16 processors requires ~4 x 48hr jobs; the fine mesh models run ~14 times as slowly, hence main parametric study done with baseline model (~10 parameters, x3 cases each = 30 simulations, as reported previously).
- The “scaled-up” model has a total of 8.3M cells, simulation of 72 minutes test using 125 processors requires ~40 x 48hr jobs on ARCHER2 (x 6 parametric variants = ~10,000 CU); hence the running speed per cell per processor per minute test time is 30% of that for the single crib, mainly due to greater complexity of the fire.



Conclusions (3)

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- A scaled-up stick-by-stick CFD model for fire spread within the large compartment of 15.2m x 9.2m x 2.8m, again demonstrates a promising capability in predicting the evolution of fire spread and burn-away as well as in reproducing main features of gas phase temperatures along the fire travelling trajectory; nevertheless there are some differences in peak temperatures which arise from details in shape of simulated fire plume and again major differences in the cooling phase.

- The potential for this approach to reproduce different fire conditions with more restricted ventilation (inverse opening factors 3.2, 13.7 & 41.7) has been assessed via comparisons with TRAFIR Ulster Travelling Fire series (x3), to explore method generalisation potential/compare with phenomenological/theoretical models in terms of fuel bed heat fluxes

- When further validated, this CFD method will provide a capability for numerical "fire experiments" for exploring structural response to variations in the design parameters (e.g., ventilation conditions, fuel arrangement, ceiling height, etc.), which are generally out of reach via conventional large-scale structural fire tests under travelling fires.

Acknowledgements (1)

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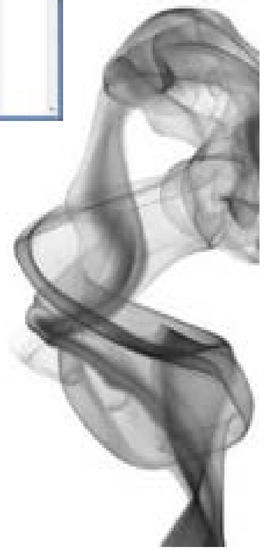
UK CTRF UK CONSORTIUM ON TURBULENT REACTING FLOWS

EPSRC Engineering and Physical Sciences Research Council

archer

EPSRC EP/R029369/1: Addressing Challenges Through Effective Utilisation of High Performance Computing – a case for the UK Consortium on Turbulent Reacting Flows (UKCTRF)

https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R029369/1



Acknowledgements (2)

Fire degree project students

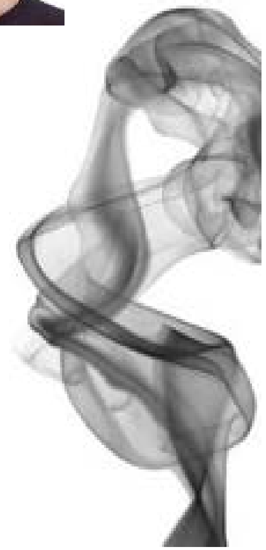
Structural and Fire Safety Engineering Dissertation (90 credits)
MEng thesis (50 credits)


19/20 students

- Chang Liu (SAFE), Yang Xu (SAFE)


20/21 students

- Peter Charley (MEng); Chang A. Liu (SAFE)

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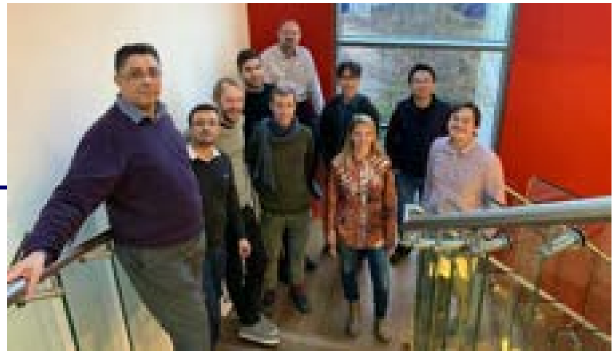
- Weitian Lu (SAFE), Yanchi Mo (SAFE)

22/24 students

- Bo Gunnarsson (MEng);
- Qianzhuo Zhou (SAFE)


Acknowledgments (3)



TRAFIR Project

Characterization of TRAvelling FIRes in large compartments

Funding from the Research Fund for Coal and Steel (RFCS) - European Commission

Industrial led – ArcelorMittal
(1/07/2017 → 31/12/2020)

- **testing** (isolated elements and simplified fire progression, as well as a full-scale large compartment)
- **modelling** (both simplified analytical/phenomenological models and CFD).

Project partners:

ArcelorMittal · Université de Liège · RISE · Ulster University · The University of Edinburgh

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Edinburgh fire

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- **Colleagues and students:**
  - 7 Academic Staff (+1 retired)
  - 5 Research staff
  - c. 20 PhD Students
  - 25+ MSc students
  - ~10 pa UG students
  - Visiting researchers
- **External Relationships:**
  - EPSRC
  - ArcelorMittal (RFCS TRAFIR project)
  - BRE Trust (FireGrid, PhD Intelligent Egress)
  - Fire & Rescue Services
  - International academic/research partn
    - UQ (Hidalgo, Maluk, Lange, Gupta…)
    - CVUT Prague (Wald, Horová…)
    - RISE (Sjöström, …)
    - Liège (Franssen, Gamba…)
    - Ulster (Nadjai, Alam…)


Questions?