The challenge of scaling-up wood crib fire experiments to travelling fires in large compartments

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THE UNIVERSITY of EDINBURGH

UKCTRF Annual Meeting
Imperial College, London
11 September 2019
Topics

• “Scaling-Up” fire*
• Crib/travelling fire experiments
  o Classical literature (Thomas, Harmathy…)
  o BST/FRS Large Compartment test 1993
  o Edinburgh Travelling Fire Test (ETFT) 2013
  o Uni Liège “Marchienne” tests 2018
  o Uni Ulster TRAFIR tests 2019
• Applications

Figure 9.2  The effect of enclosure on the rate of burning of a slab of polymethylmethacrylate (0.76 m × 0.76 m) (Friedman, 1975)
Figure 10.2  Variation of mass burning rate with $A_w H^{1/2}$ for large ventilation openings and different fire loads (wood cribs): ✦, 7.5 kg/m²; ⚫, 16 kg/m²; ⭐, 30 kg/m²; ○, 60 kg/m². Dashed line (---) represents Equation (10.1) for the ventilation-controlled fire (Thomas et al., 1967a). Reproduced by permission of The Controller. HMSO. © Crown copyright.
Burning rates – timber cribs

Figure 10.5 Identification of the transition between ventilation-controlled and fuel-controlled burning for wood cribs, according to Harmathy (1972)

Burning rates – timber cribs

This behaviour is not intuitive, as the fuel burning rate should depend on compartment interaction, see Fig 9.2, not purely on oxidant supply; the reason may be partly the unique nature of fuel bed with the shielded internal fuel surfaces…

Figure 10.1 Mass burning rate of wood cribs in enclosures as a function of the ventilation factor, $A_w H^{1/2}$ for ventilation-controlled fires (Equation (10.1)): ●, full-scale enclosures; ○, intermediate-scale models; □, small-scale models (Kawagoe and Sekine, 1963). Reproduced by permission of Elsevier Applied Science Publishers Ltd
Temperature correlation (1)

Figure 10.6  Average compartment temperatures during the steady burning period for wood crib fires in model enclosures as a function of the ‘opening factor’ $A_T/A_w H^{1/2}$. Symbols refer to different compartment shapes (see Table 9.3): ○, $1 \times 2 \times 1$; Δ, $2 \times 2 \times 1$; ◊, $2 \times 1 \times 1$; □, $4 \times 4 \times 1$. Solid points are means of 8–12 experiments (Thomas and Heselden, 1972). Reproduced by permission of The Controller, HMSO. © Crown copyright
Temperature correlation (2)

Figure 4. The relationship between the inverse opening factor $A_T/(A_w H^{1/2})$ and the measured maximum average gas temperature $T_{g,max}$ near ceiling level of test large compartments, through reviewing previous large-scale natural fire tests with a clear travelling fire development, performed in the past three decades. (solid curve in blue is the 2nd order polynomial regression line for all the reviewed travelling fire tests, and dashed red curve is the same curve presented in Figure 3 for small size compartments as a reference; the translucent blue band describes a bootstrap confidence interval of the estimated regression line according to the available data sampling points).

Burning rates – timber cribs

The Post-flashover Compartment Fire

Figure 10.7  The effect of a large exposed fuel surface area on fire behaviour. (a) Fuel control regime, 15 kg/m². Fuel in the form of wood cribs, $A_f = 55$ m²: no external flaming. (b) Ventilation control regime, 7.5 kg/m². Fuel was fibre insulating board, lining the walls and ceiling, $A_f = 65$ m²; external flaming lasted for 5.5 minutes (Butcher et al., 1968). Reproduced by permission of The Controller, HMSO. © Crown copyright

the other. In the former, the wood was present in the form of cribs (with a surface area of 55 m², including the internal surfaces – see Figure 5.20), while in the other it was present as the wall lining material (exposed surface area 65 m²) (Butcher et al., 1968). The large area of fuel directly exposed to the fire in the latter case produced flashover followed by Regime I burning with flames emerging from the window, while the wood cribs burned as a fuel-controlled fire (Regime II). Harmathy’s method (Equation (10.18)) does not distinguish between these two scenarios.
Travelling fires

• Ultimate application is structural fire design
• Breaking out from highly oversimplified techniques
• Spatially and temporally varying boundary conditions
• OpenSees framework

**TRAfIR Project**
Characterization of TRAvelling FIRes in large compartments

Funded by Research Fund for Coal and Steel (RFCS)/European Commission

Full-scale tests, simulations, etc. (1/07/17→31/12/20)
BST/FRS large compartment, 1993

- **Date:** 1993 at Building Research Establishment (BRE), UK
- **Team:** BRE (Fire Research Station)/British Steel Technical (Swinden Laboratories)
- **Aim:** generating experimental data to validate the ‘Time Equivalent’ formula in Eurocode 1 for buildings with large/deep compartments, or large open plan offices

Fig. 1. (a): Test compartment of the BST/FRS 1993 Fire Test Series (22.8m × 5.6m × 2.75m); (b): Ignition of the first row of wood cribs in test number 2, front view; (c): Layout of the wood cribs distribution within the test compartment in plan view.

### BST/FRS large compartment, 1993

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Test 7</th>
<th>Test 8</th>
<th>Test 9</th>
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<tr>
<td>Compartment Size</td>
<td>Full size</td>
<td>Full size</td>
<td>Full size</td>
<td>Full size</td>
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<td>Full size</td>
<td>½ size</td>
<td>Full size</td>
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<tr>
<td>Walls and Ceiling Lining</td>
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<td>Ceramic fibre</td>
<td>Ceramic fibre</td>
<td>Ceramic fibre</td>
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<td>Ceramic fibre</td>
<td>Plaster-board</td>
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<tr>
<td>Fire Load Density, kg/m³ of Floor</td>
<td>40</td>
<td>20</td>
<td>20</td>
<td>40</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20.6</td>
<td>20</td>
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<td>Ventilation ×</td>
<td>1/1</td>
<td>1/1</td>
<td>1/2</td>
<td>1/2</td>
<td>1/4</td>
<td>1/8</td>
<td>1/4</td>
<td>1/1</td>
<td>1/1</td>
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<td>380.1</td>
<td>380.1</td>
<td>759.9</td>
<td>380.1</td>
<td>380.1</td>
<td>380.1</td>
<td>402.3/507.2</td>
<td>380.1</td>
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<td>Growing</td>
<td>Growing</td>
<td>Growing</td>
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<td>Growing</td>
<td>Simultaneous</td>
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BST/FRS large compartment, 1993

* Schematics c/o Gordon Cooke, from presentation at Structures in Fire Forum (STiFF), IStructE, London, 2017
FDS simulation test no.2

FDS model side view 1

FDS model side view 2

FDS model, view with outlines only
Comparison of thermocouple (TC) temperatures between test and model

(a) Three locations - TC temperatures at ceiling height

(b) Ignition side - TC temperature at ceiling height

(c) Centre of the compartment - TC temperature at ceiling height

(d) Opening side - TC temperature at ceiling height
Comparison of gas concentrations between test and model (oxygen concentration test data at rear compartment invalid after 7 mins, due to pipe leakage)

Fire spread in crib fire tests (ETFT)

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, Uni Ulster, 6-8 June 2018
Travelling fire simulations

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, Uni Ulster, 6-8 June 2018
“Lige test series”, Marchienne, 2018

- Isolated crib fire test series:

<table>
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<tr>
<th>Date</th>
<th>Test ID.</th>
<th>Section*</th>
<th>Orientation</th>
<th>Number of layers</th>
<th>Centre to Centre</th>
<th>Total height</th>
<th>Roof</th>
<th>Ethanol 96%</th>
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<td>M1</td>
<td>1</td>
<td>-</td>
<td>6</td>
<td>80</td>
<td>209</td>
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<td>40</td>
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<tr>
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<td>M2</td>
<td>2</td>
<td>-</td>
<td>6</td>
<td>135</td>
<td>285</td>
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<td>40</td>
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<tr>
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<td>M3</td>
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<td>-</td>
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<td>418</td>
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<td>40</td>
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<td>30/08/18</td>
<td>M4</td>
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<td>-</td>
<td>3</td>
<td>135</td>
<td>247</td>
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<td></td>
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<td>□</td>
<td>4</td>
<td>80</td>
<td>234</td>
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<td>40</td>
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</table>

1) Orientation = | means that the stick was placed with L1 of 30 mm on the ground so you have a height of 35mm
2) Orientation = - means that the stick was placed with L2 of 35 mm on the ground so you have an height of 30mm
3) Orientation = □ means that the stick was used with latches because L1 = L2

- Why M7?

Reason: larger stick spacing (i.e. better porosity) allow larger grid cells in FDS. Also a medium fire spread, close to target…
Wood sticks layout in plan view (dimension units mm):

“Liege test series”, Marchienne, 2018
“Liege test series”, Marchienne, 2018

- Wood sticks layout in elevation view 1 (dimension units mm):
Wood sticks representation, and coordinate system, in elevation:

50mm offset for the ignition burner & steel tubes

“Liege test series”, Marchienne, 2018
"Liegé test series", Marchienne, 2018

- Wood sticks representation, and coordinate system, in plan view:

Wood stick distribution as a circle, diameter 3.6m

NB – wood sticks in FDS must be arranged orthogonally!
“Liege test series”, Marchienne, 2018

- Fire spread in terms of $t$ squared format:

Radius of the fire (m) | Tests made in Marchienne-au-Pont
--- | ---

- $t_\alpha = 2.5$
- $t_\alpha = 3.9$
- $t_\alpha = 7.3$
- $t_\alpha = 7$
- $t_\alpha = 9.4$

Tests made in Marchienne-au-Pont:
- 30x35 : 12 layers
- 35x45 : 5 layers + PMMA
- 30x35 : 6 layers + 15x15 laths
- 30x35 : 9 layers
- 30x35 : 6 layers
- 30x35 : 6 layers

Time [s] 1800
MPI used, 11 meshes in total, cell size $0.03m \times 0.03m \times 0.035m$ (to fit per cell - per cross section) for wood sticks; cell size $0.06m \times 0.06m \times 0.07m$ for upper flame and ceiling part; total number of cells 670 320
Babrauskas model works when fire diameter is larger than 0.2m. However, our ethanol ignitor has diameter 0.106m only. Based on Fig.1 from Babrauskas 1983 paper, we are over-estimating the HRRPUA of our burner, resulting to a shorter burning time. Any free ethanol burning test so we can get the time duration? @Antonio
FDS simulation “Liège test series” M7

Spruce wood material model, FDS input script

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<td>'Density measured by ULG, HC from SFPE (times 0.8) p.3449, Cond &amp; SH from Pei Xing Yang'</td>
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<td>'RAMP ID = 'PICEA_SH_RAMP', ( T = 1200.0, p = 1.65)'</td>
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NB – only wood density is known. Heat of combustion (20.4×0.8=16.32MJ/kg) is from SFPE Handbook with assumed combustion efficiency 0.8; specific heat and conductivity RAMP from fit by Yang (2016) IMFSE thesis

FDS simulation “Liège test series” M7

Wood SURF & HRRPUA, FDS input script

HRRPUA 223kW/m² is from fit in Yang’s work, accompanying with per stick (50mm×50mm ×1000mm) is 20MJ, the RAMP_Q can be estimated.
Spruce (*Picea abies*) characterisation in bomb

Bomb calorimetry for heat of combustion (gross)

The gross chemical heat of combustion of Spruce (*Picea abies*), is **18MJ/kg**, very small amount of sample (i.e. around 0.5g) tested in bomb calorimeter.
Spruce (*Picea abies*) characterisation in cone calorimetry for critical flux, ignition temperature, burning rate, etc.
Heat of combustion value is updated according to the ‘Picea abies’ wood sample test at UEDIN using bomb calorimeter. Gross chemical heat of combustion (HoC) is 18MJ/kg. According to relationship between gross HoC and net HoC of spruce from Table A.32 in SFPE Handbook, net HoC of Spruce \((Picea abies)\) is estimated as \((20.4 \times 18)/21.8 = 16.84\text{MJ/kg}\), assuming combustion efficiency 0.8 the effective HoC is estimated as \(16.84 \times 0.8 = 13.48\text{MJ/kg}\).
FDS simulation “Liège test series” M7

Multi-mesh in elevation view, mesh number 30 in total, cell size 0.03m × 0.03m × 0.035m (to fit per cell - per cross section) for wood sticks, total number of cells 2,201,472 (HPC on ARCHER via UKCTRF)
FDS simulation “Liège test series” M7

Multi-mesh in elevation view, mesh number 30 in total, cell size $0.03\text{m} \times 0.03\text{m} \times 0.035\text{m}$ (to fit per cell - per cross section) for wood sticks, total number of cells 2,201,472 (HPC on ARCHER via UKCTRF)
FDS simulation “Liège test series” M7

FDS model front view

FDS model, side view

FDS model top view
FDS simulation “Liège test series” M7

60s from test (at 20min of the full test video is regarded as t=0s)

60s from FDS

120s from test

120s from FDS
FDS simulation “Liège test series” M7

180s from test

180s from FDS

240s from test

240s from FDS
FDS simulation “Liège test series” M7

300s from test

300s from FDS

360s from test

360s from FDS
FDS simulation “Liège test series” M7

420s from test

420s from FDS

468s from test

468s from FDS
How fire spreads among the wood stick layers

FDS simulation “Liège test series” M7

120s from FDS

240s from FDS

360s from FDS

468s from FDS
FDS simulation “Liège test series” M7

BUT, despite superficial agreement on spread, the HRR & MLR from FDS is twice that of the test!
FDS simulation “Liège test series” M7

Issues spotted towards end of simulation

The fire plume is not well developed in this early version of FDS model, compared with the test at 860s; again, the fire spread rate in the model is much faster than the test.
FDS simulation “Liège test series” M7

Issues spotted towards end of simulation

The fire plume is not well developed in this early version of FDS model, compared with the test at 860s; again, the fire spread rate in the model is much faster than the test.
FDS simulation “Liège test series” M7

Examination of burn-out

Key constraint – match of burn-out i.e. a doughnut-like burning format is observed in the model.
FDS simulation “Liège test series” M7

Significant challenge in calibrating mass loss rate – possibly due to over-simplified wood stick representation in the FDS model

Shifted fuel load arrangement for test M7; Test M7 is made of 9 layers of sticks with an axis distance of 120 mm, layers i and i+3 were shifted laterally by 60 mm.

In the FDS model, we have no offset, hence less porosity (i.e. lower layers support reduced fire spread).
A demo with chop sticks… 😊

The overall aim is to increase porosity of wood crib to boost fire spread at lower layers.

Wood sticks in the proposed FDS model

ULG, M7 test
Now every 2 layers we have the *wood sticks ‘offset’ in parallel distance of 60mm*, to generate higher porosity for FDS model, v4 series. Multi-mesh shown below.
FDS simulation “Liège test series” M7

HRR comparison between test and FDS, for M7

Note: with new wood arrangement in FDS model v4.1, this t-squared fire development in terms of HRR, or MLR becomes unclear or even diminishes. This wood stick rearrangement is not successful!
FDS simulation “Liège test series” M7

Why chessboard model?

Advantages:
- larger grid cells
- consistent mass/air ratio
- still uniform fuel bed

Disadvantages:
- worse fuel-bed resolution
- unknown reliability of this method
FDS simulation “Liège test series” M7


Updated M7 calibration with chessboard method
FDS simulation “Liège test series” M7

HRR comparison between test and FDS, for M7

Extremely difficult to match the full behaviour of the fire, i.e. spread, HRR, MLR, temperature, etc.
FDS simulation “Liège test series” M7

FDS modelling animation

HRR: 0.0 W
Time: 0.0
FDS simulation “Liège test series” M7
After extensive series of trials finally achieving a better qualitative matching to the observed fire spread behaviour

FDS simulation “Liège test series” M7
Remaining discrepancy is HRR, seems we need to explicitly consider the link to the fire exposure (but crib fire plots from Drysdale had suggested otherwise!)
Ulster University TRAFIR fire tests

Photo © University of Ulster
https://www.bbc.co.uk/news/uk-northern-ireland-48707462
A priori simulation, Ulster TRAFIR #1

- All input parameters for this *a priori* model (e.g. HRRPUA, ignition temperature, material properties, etc) are based on M7 model

At this stage of the simulation, the model is still comparable to the test, based on the observations on test site.
A priori simulation, Ulster TRAFIR #1

- All input parameters for this *a priori* model (e.g. HRRPUA, ignition temperature, material properties, etc) are based on M7 model.

  - 1700s
  - 1900s
  - 2000s
  - 2080s

However, after 1500s the agreement diverges, presumably because the burn-away function in the model was not properly resolved in the previous M7 calibration!
ETFM framework application, TRAFIR #1

- Structural & fuel layout similarity between TRAFIR-RISE natural fire test (Dec-18), and TRAFIR-Ulster Travelling Fire Test No.1, ETFM framework “calibrated” with RISE test

TRAFIR-RISE wood crib fire test vs. ETFM framework modelling
Then assuming the fire spread rate in the Ulster Travelling Fire Test No.1 is 2mm/s, based on the M7 test observation between 10-20mins...
Conclusions (1)

- Methods of representing a crib fire using simplified fuel representations (coarser sticks, and different stick arrangements) are being explored;
- The models tend to have a highly over-simplified treatment of the flow within the crib, as there is insufficient grid resolution;
- Simplified ‘engineering’ models of burning behaviour are postulated to overcome this;
- Direct measurement of required reaction-to-fire properties obtained from relevant bench-scale tests;
- It proves to be very challenging to replicate full-scale fire development with the simplified models, where spread, HRR, MLR and burn-out all provide validation constraints;
- Nevertheless, latest results with a finer mesh within the depth of the crib, are closer to satisfying the set of constraints;
- A reasonable case can be made that grid resolutions should be different in the bulk flow and within the crib structure itself;
- Fire spread in the depth of the crib is much harder to assess as it is difficult to observe in the test, however it is generally slower than surface spread;
Conclusions (2)

- Application to full-scale scenarios is ongoing, taking the “validated model” from crib fire experiments and performing *a priori* simulations of travelling fire tests in a 15x9x2.8m compartment (series of tests with 3 different opening factors);
- Some success in prediction of early spread but still tendency for run-away later in test;
- The challenge of fire spread prediction compounds existing difficulties in representing fire temperatures in post-flashover/under-ventilated conditions (e.g. BST/FRS 1993);
- Further difficulties in representing conditions in *cooling* phase of fire, where mass loss data is absent/unreliable;
- Despite the challenges in travelling fire prediction, including both spread and burn-out, the technology has great potential in representing the interaction of the fire and the structure;
- This will assist in providing engineers with simple and practical methodologies for structural fire design;
- Work is supported by and done in close cooperation with industrial partners (ArcelorMittal), with EU funding via RFCS;
- UKCTRF support has been vital in enabling more simulations.
TRAFIR Project
Characterization of TRAavelling FIRes in large compartments

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

Eight work packages (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
• Colleagues and students:
  10 Academic Staff (+1 retired)
  6 Research staff
  c. 20 PhD Students
  40+ MSc students
  5-10 pa UG fire students
  Visiting researchers

• External Relationships:
  • UKCTRF
  • EPSRC
  • ArcelorMittal (Charlier, Vassart…)
  • BRE Trust
  • Fire & rescue services
  • International academic/research partners
    • UQ (Hidalgo, Maluk, Lange, Gupta…)
    • CVUT Prague (Wald, Horová…)
    • RISE (Sjöström, Anderson…)
    • Liege (Franssen, Gamba…)
    • Ulster (Nadjai, Alam …)
A group of leading academics from 19 United Kingdom institutions have been joined by internationally recognised experts to form UKCTRФ. As a consortium, they will make a focussed effort to address the global and UK challenges of energy efficiency, environmental friendliness and high-fidelity fire safety.
Questions?
Appendix – computational expenses

Summary of computational expenses of initial models on ARCHER, c/o UKCTRF

Note: this is just a summary rather than a benchmarking for ARCHER, we don’t want to consume more than 150kAUs per job at this stage of TRAFIR WP4