Structural response of steel-composite structures in under-ventilated travelling fires: numerical insights from the BST/FRS 1993 Fire Tests

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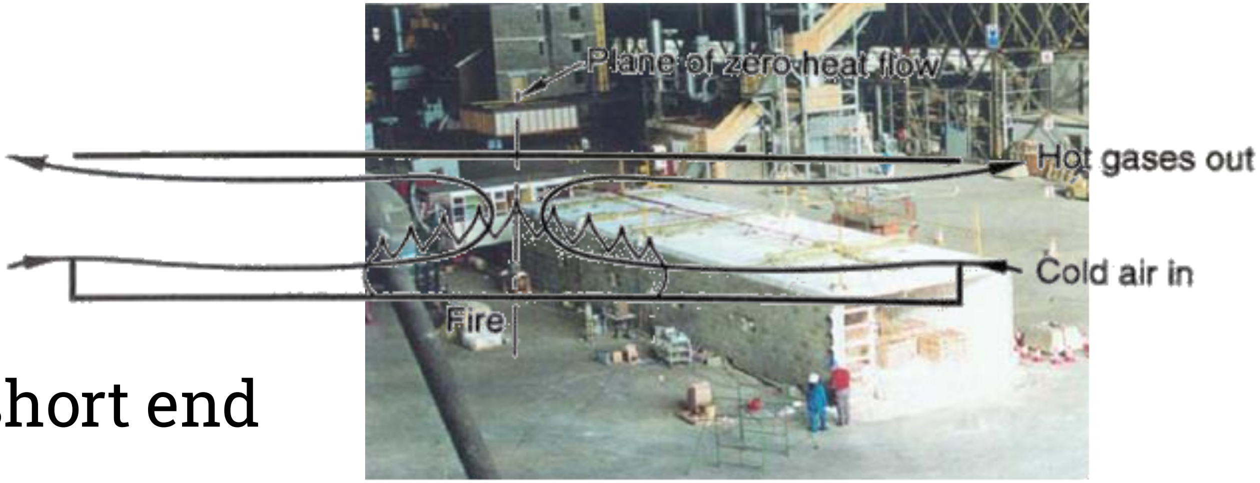
The BST/FRS 1993 Fire Test Series

Nine tests with varied **fuel loads & ventilation conditions**

conducted by British Steel Technical (BST) & Fire Research Station (FRS) at the BRE Cardington laboratory **to simulate the behaviour of natural fires in large-scale compartments** [1].

- Compartment dimensions:
  22.8m (L) × 5.6m (W) × 2.75m (H)
- Fuel load: Discrete wood cribs
- Ventilation: Single opening at one short end



Designed to represent a ‘slice’ of a larger compartment with infinite width

Opening represents a small piece of a long ‘window wall’ in building

[1] Kirby BR, Wainman D, Tomlinson LN, Kay T, Peacock BN (1999) NATURAL FIRES IN LARGE SCALE COMPARTMENTS. In: International Journal on Engineering Performance-Based Fire Codes. pp 43–58

Test selection & Key parameters

Investigate effects of ventilation conditions and fuel load density on fire

*Summary of key parameters in **Tests 1-6***

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Compartment Size	Full size	Full size	Full size	Full size	Full size	Full size
Walls and Ceiling Lining	Ceramic fibre	Ceramic fibre	Ceramic fibre	Ceramic fibre	Ceramic fibre	Ceramic fibre
Fire load density, kg/m² of Floor	40	20	20	40	20	20
Ventilation ×	1/1	1/1	1/2	1/2	1/4	1/8
Ventilation Factor, w_f	1.4795	1.4795	2.3087	2.3087	2.9396	3.2760
Fire load density, q_f (MJ/m² of Floor)	759.9	380.1	380.1	759.9	380.1	380.1
Ignition/Fire Progress*	Growing	Growing	Growing	Growing	Growing	Growing

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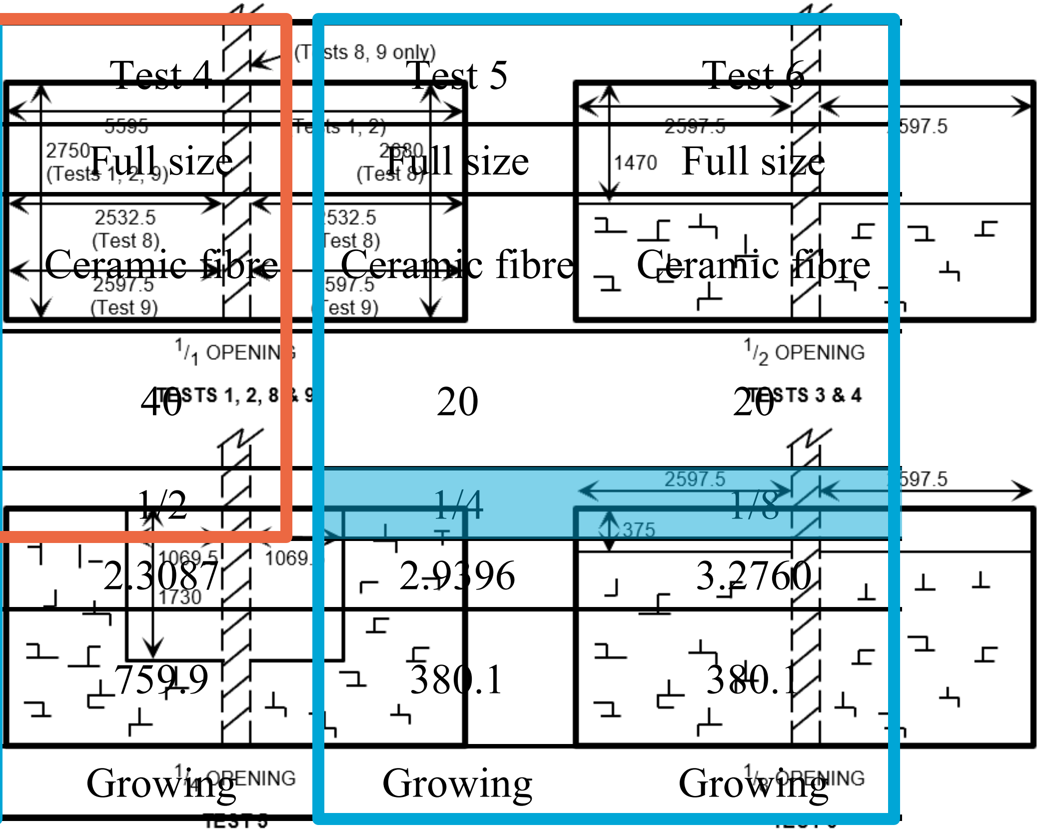
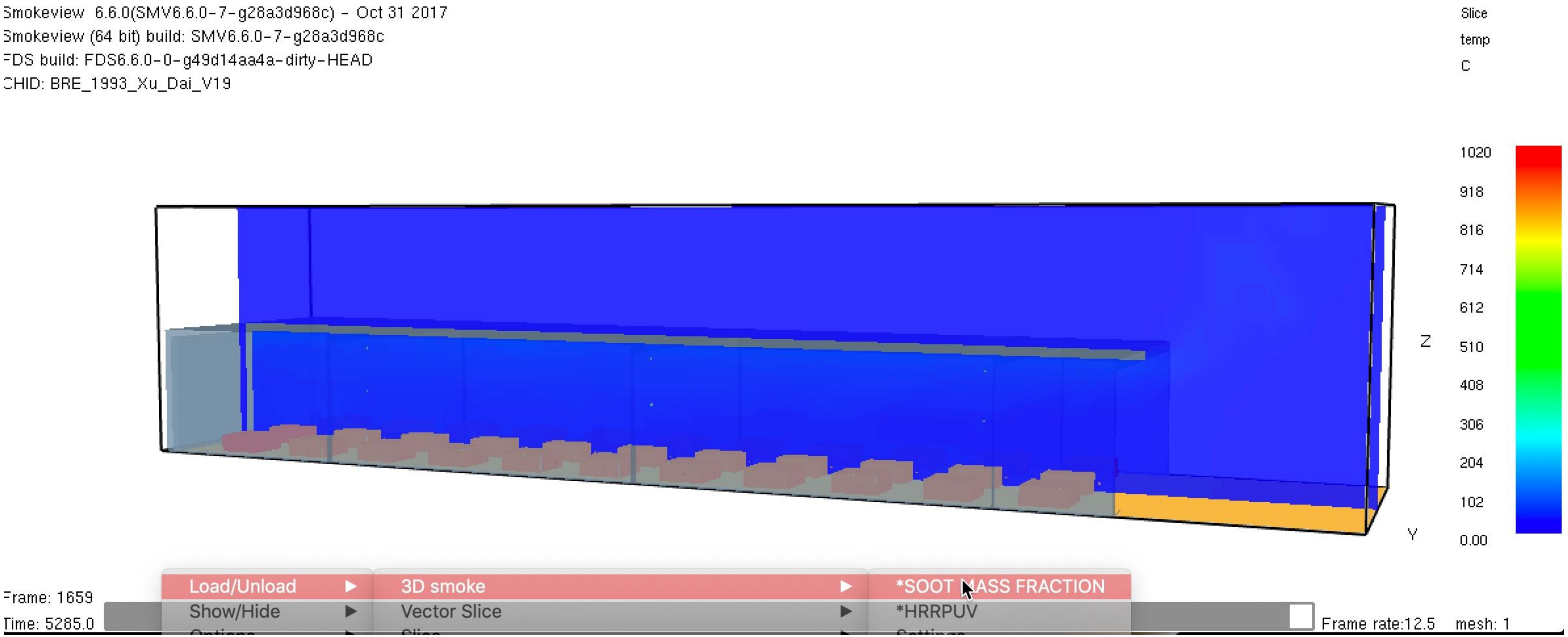


Typical fire development pattern

FDS simulation replicated the fire spread observed in Test 2



X. Dai*, S. Welch, D. Rush, M. Charlier, J. Anderson, Characterising natural fires in large compartments – revisiting an early travelling fire test (BST/FRS 1993) with CFD, 15th International Interflam Conference, July 2019, London, UK, pp2111-2122.

Typical fire development pattern

- Initial ignition

Fire grew and spread to adjacent fuels slowly

- Rapid develop

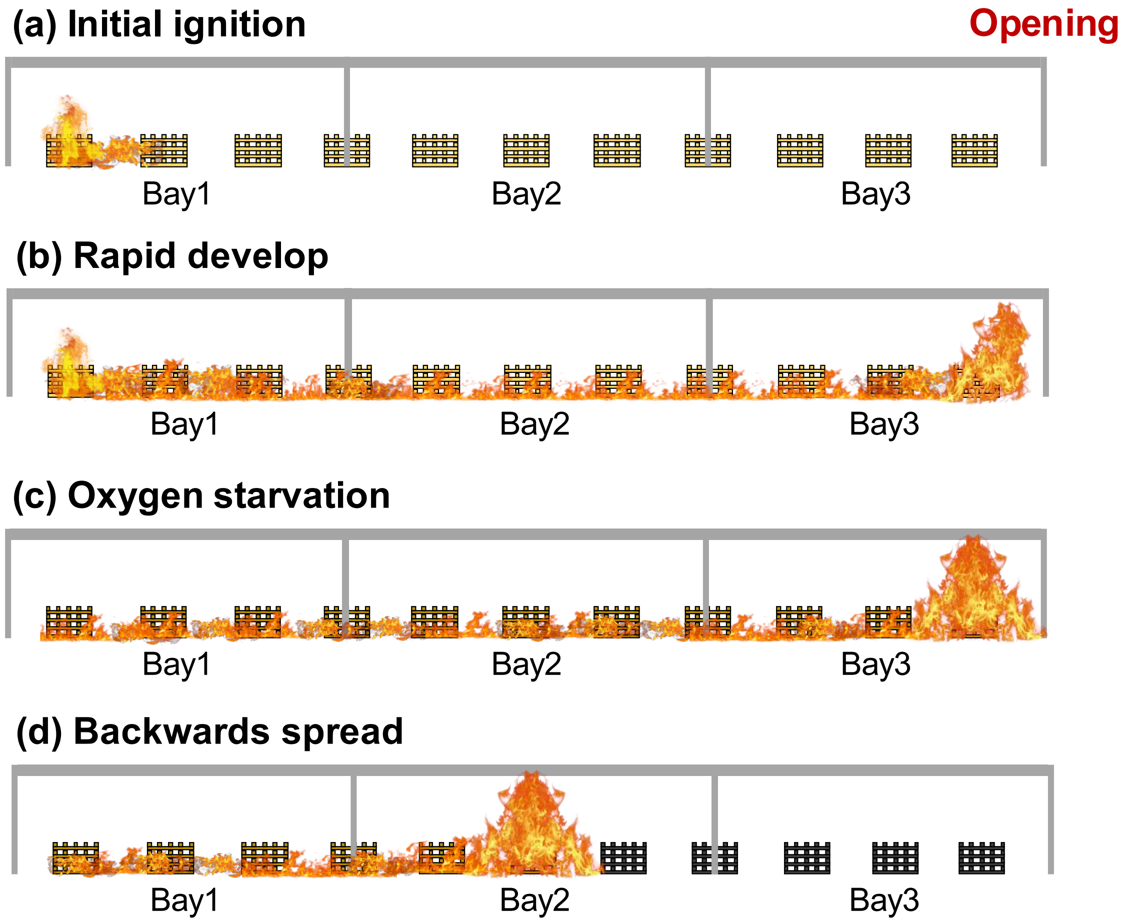
Fire developed rapidly towards the opening

- Oxygen starvation

Once fully developed, combustion in middle-to-rear was suppressed

- Backwards spread

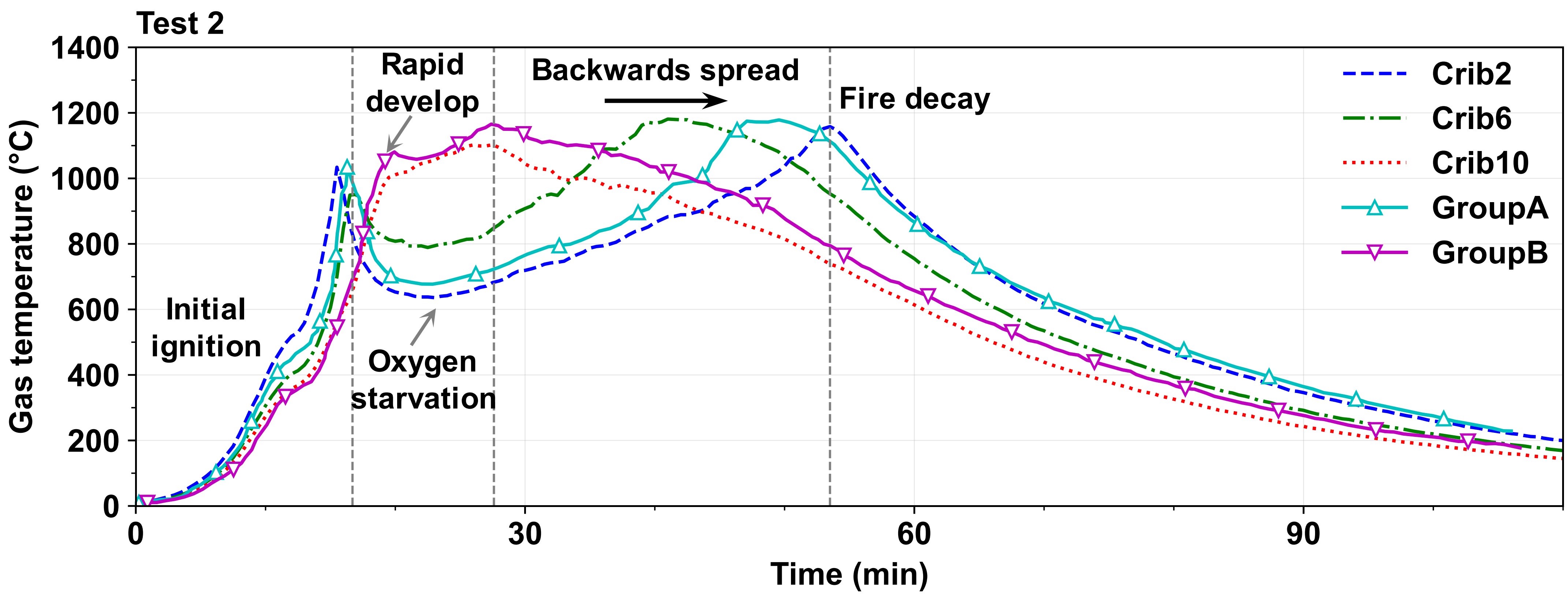
As fuel near opening was consumed, fire spread slowly towards rear of compartment



Typical fire development pattern

Observed in Test 2

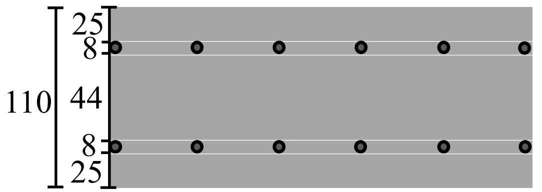
(a) Test 2 - 15.5 min Temperature (°C) (b) Test 2 - 26 min Temperature (°C)



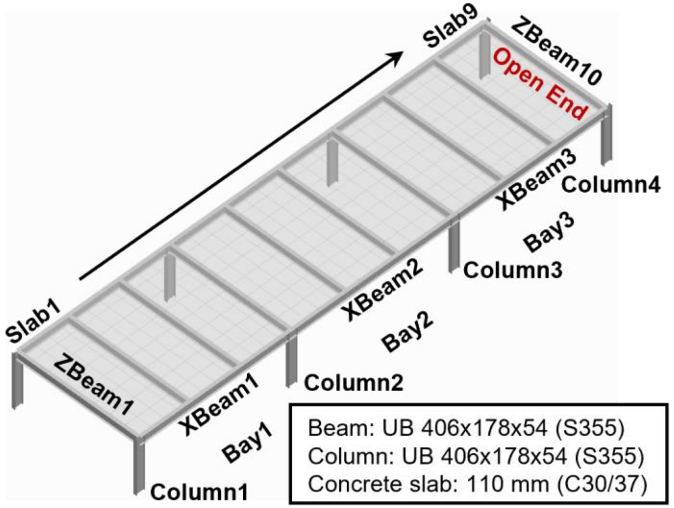
Distance from End (m) Distance from End (m)

Prototype structure

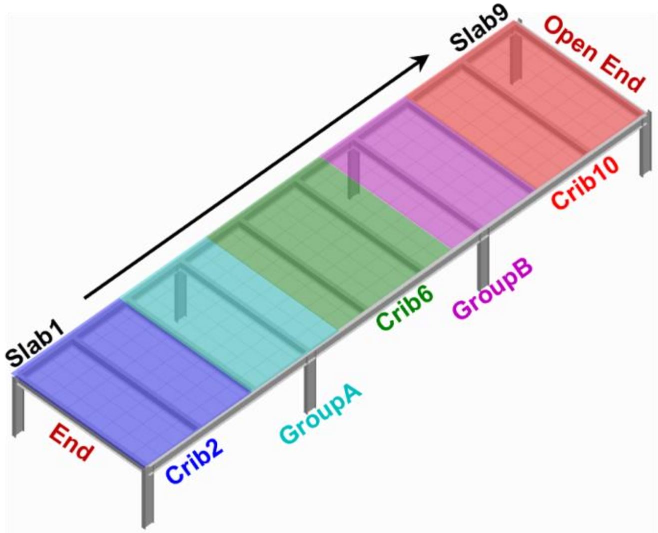
- 23m (L) × 6m (W) × 2.75m (H), Bay2 (8.0 m), Bay1 & Bay3 (7.5 m)
- Design load: 1.35×dead load+1.5×live load = 1.35×4.11+1.5×2.5 = 9.30 kN/m^2
- Load ratio: 0.7 (unfactored design loads $\gamma_G = 1$, $\gamma_Q = 1$)
- Slabs: Cofraplus 60
- Formulation of elements in LS-DYNA:
  Hughes-Liu (beam) & Belytschko-Lin-Tsay (slab)



Concrete C30/37
Reinforcement Ø8 100 mm/100 mm
490 mm^2/m 420 Mpa

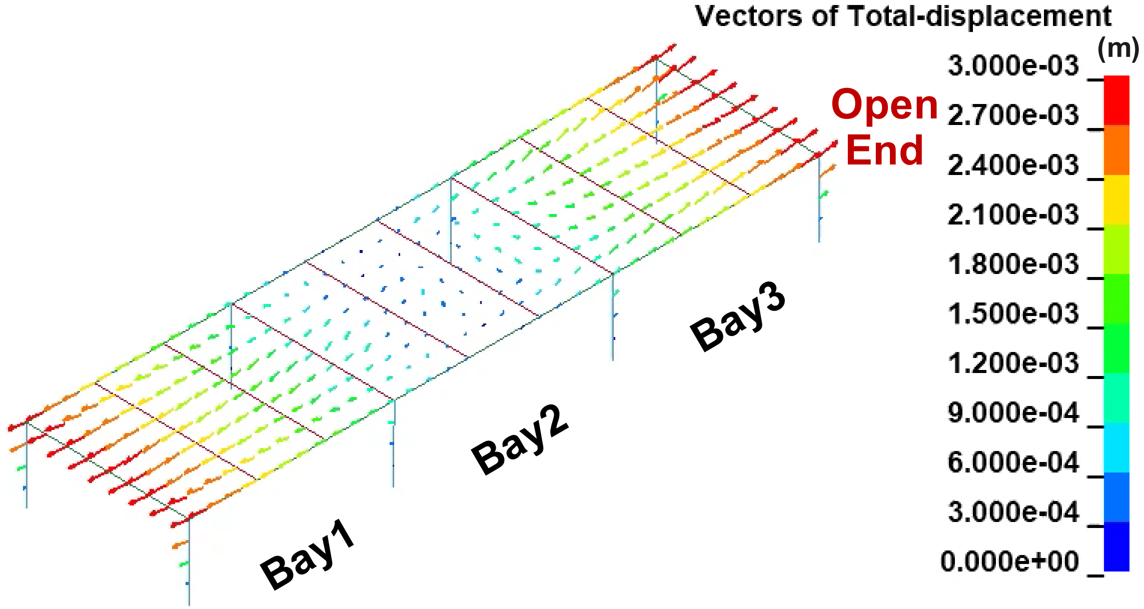


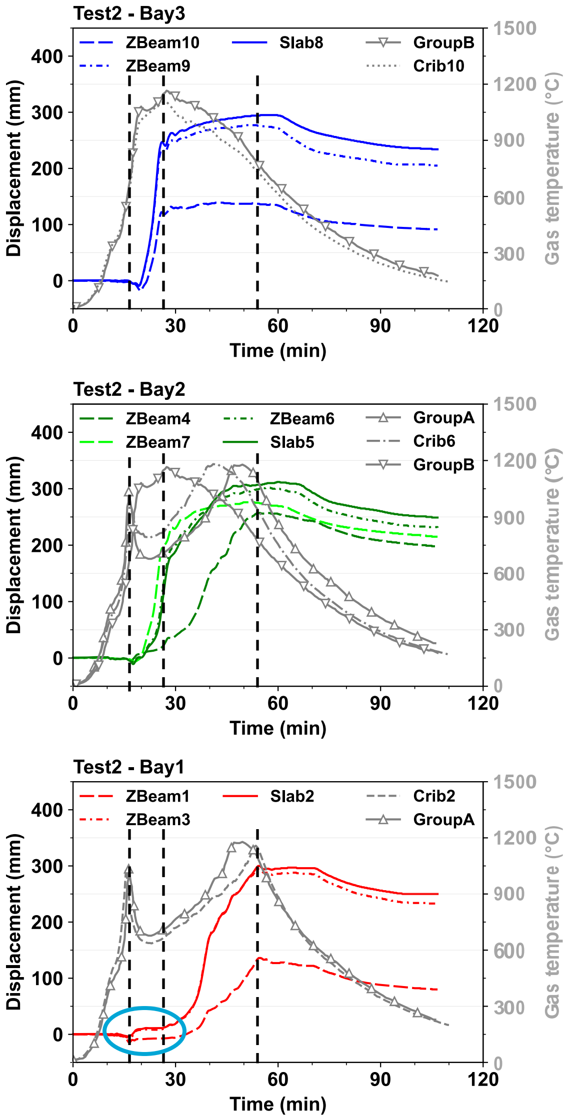
thermal load divisions

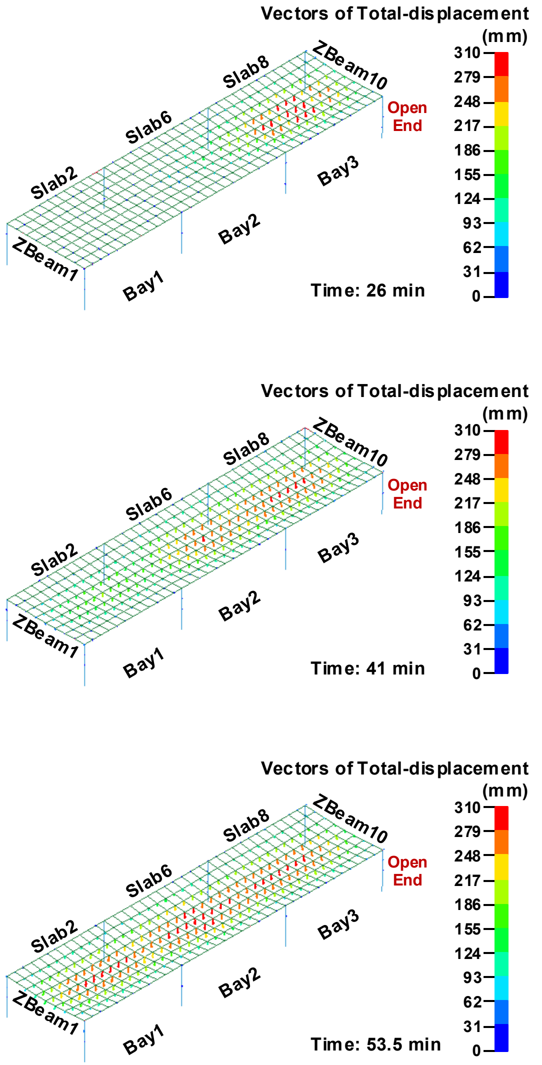


Structural response

Under travelling fire Test 2





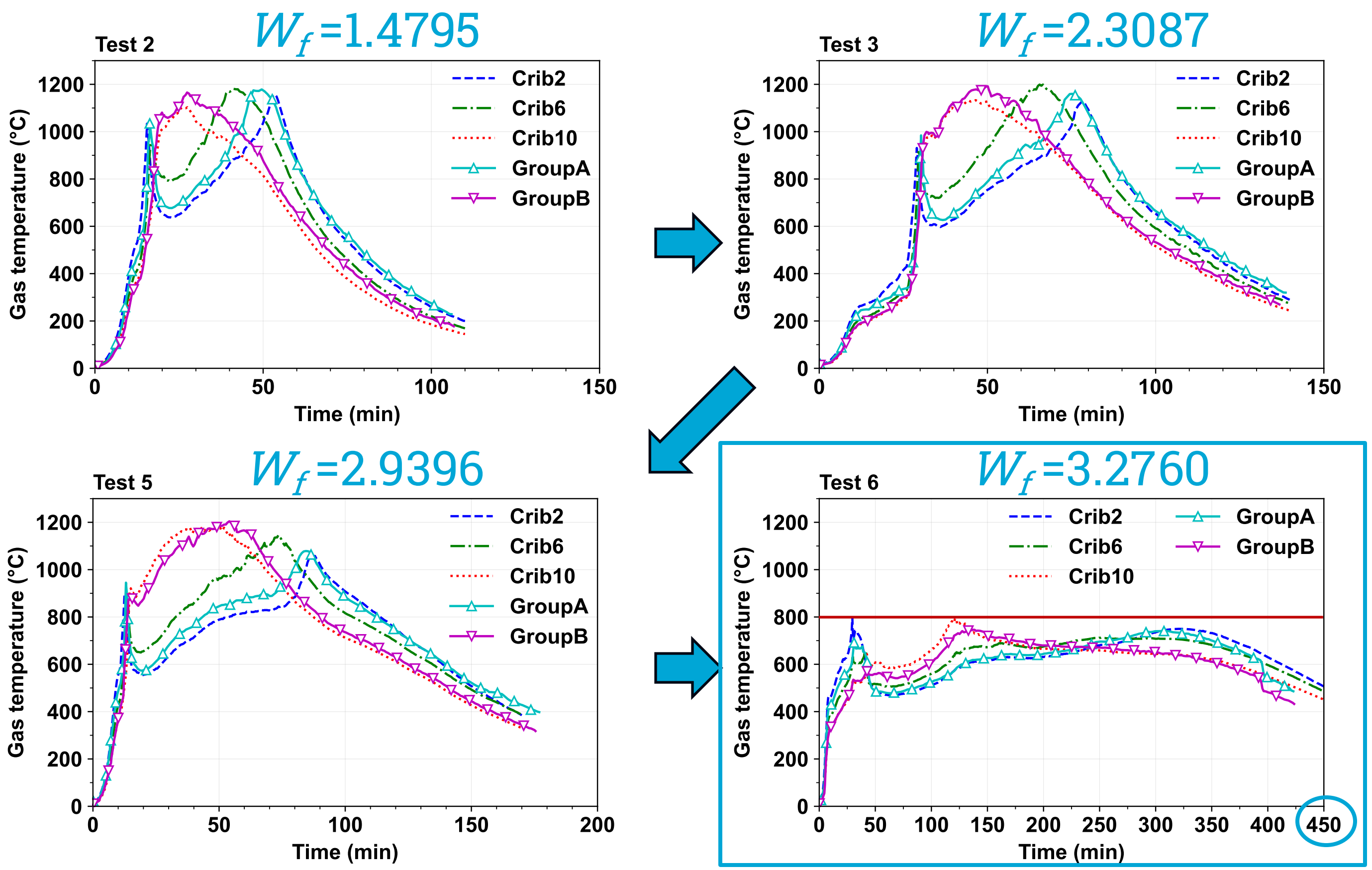


Effect of ventilation conditions

$$W_f = (6/H)^{0.3}[0.62+90(0.4-a_v)^4/(1+b_v a_h) \geq 0.5$$

On fire behaviour

- Test 2: **1/1** opening (fully opened)
- Test 3: **1/2** opening
- Test 5: **1/4** opening
- Test 6: **1/8** opening



Ventilation-controlled Fires

Fire behavior dependent on **oxygen availability**

As **opening size decreases (↓)**, **fire duration increases (↑)**.

In Test 6 (1/8 opening), the fire became severely oxygen-starved, leading to **incomplete combustion**, a significantly extended fire duration, and a drop in peak gas temperature.

Effect of ventilation conditions

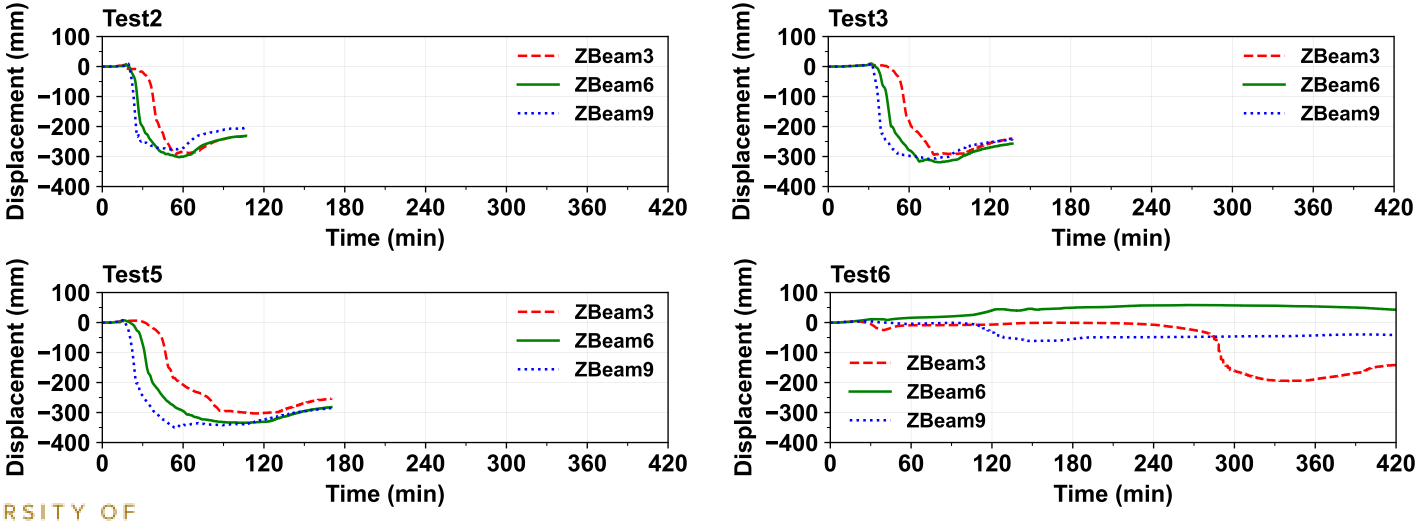
On structural fire responses

Structural fire response pattern (Tests 2, 3, 5)

Fire developed rapidly towards the opening, causing structural elements in **BAY 3** (near the opening) to heat up first, leading to the **softening and bending** of steel members.

Due to **backward fire spread**, structural elements in **BAY 2 and BAY 1** heated up sequentially.

As **opening size decreases (↓), fire duration increases (↑)**, resulting in **larger deflection** due to the extended fire duration allowing more time for heat transfer.

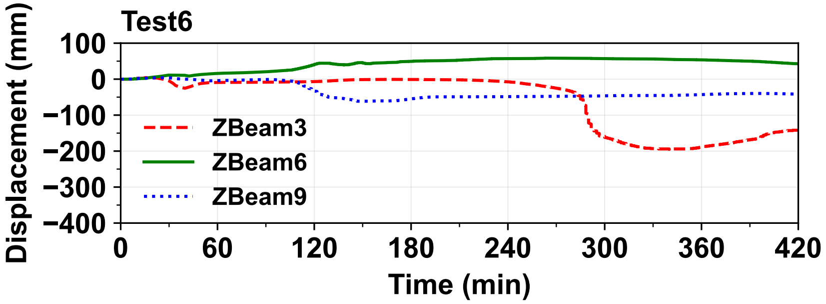


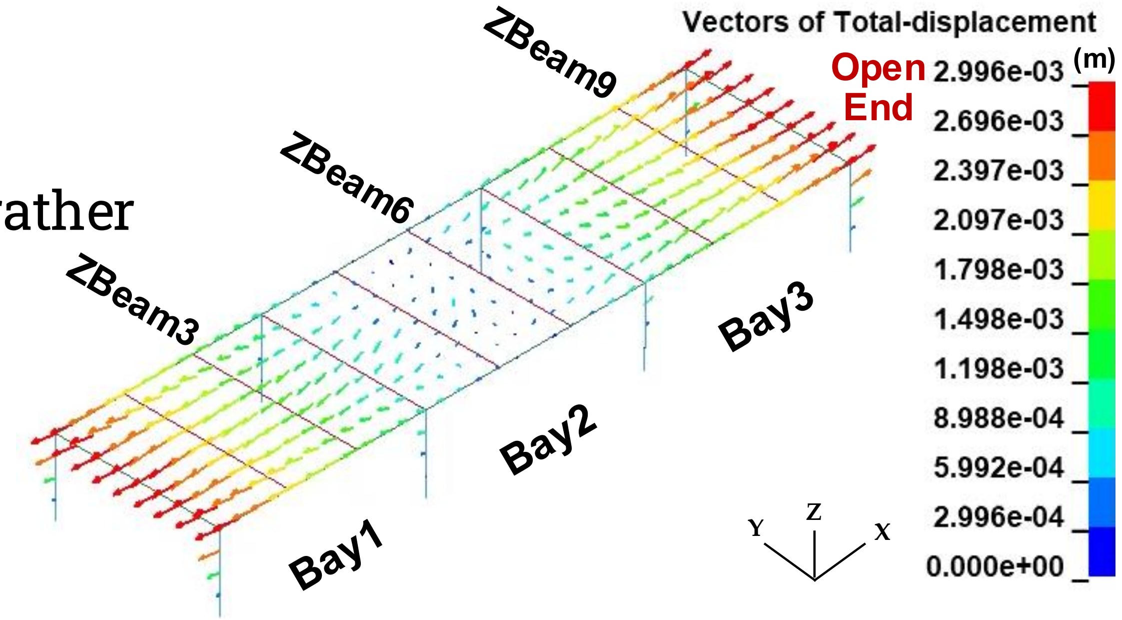
Effect of ventilation conditions

On structural fire responses

Structural fire response (Test 6)

Structural elements in BAY2 deformed upward rather than bending





Oxygen-starved fire & Incomplete combustion

Lower temperatures (<680℃) → Less steel softening → Limited bending

Extended fire duration → Less non-uniform temperature distribution

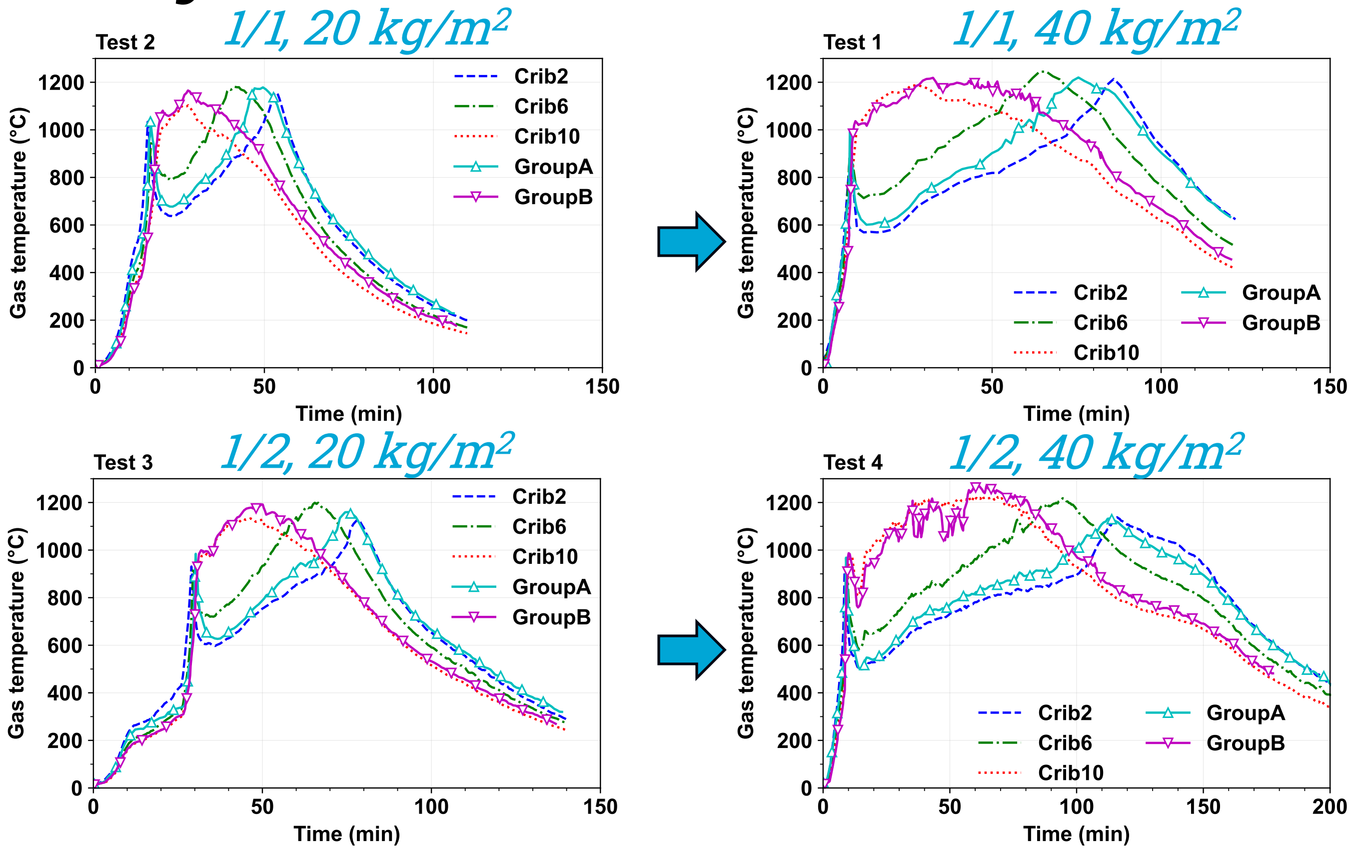
Restrained conditions in middle bay → Constrained expansion, leading to upward deformation rather than bending

Effect of fuel load density

On fire behaviour

- Test 2: **1/1** opening, fuel load density **20** kg/m²
- Test 1: **1/1** opening, fuel load density **40** kg/m²
- Test 3: **1/2** opening, fuel load density **20** kg/m²
- Test 4: **1/2** opening fuel load density **40** kg/m²

Ventilation-controlled Fires



As **fuel load density (↑), longer burning duration (↑), higher peak gas temperatures (↑)**.

Delayed backward spread (oxygen limitation slows down fire from spreading backward).

Maybe more incomplete combustion (leading to increased smoke and toxic gases).

Effect of fuel load density

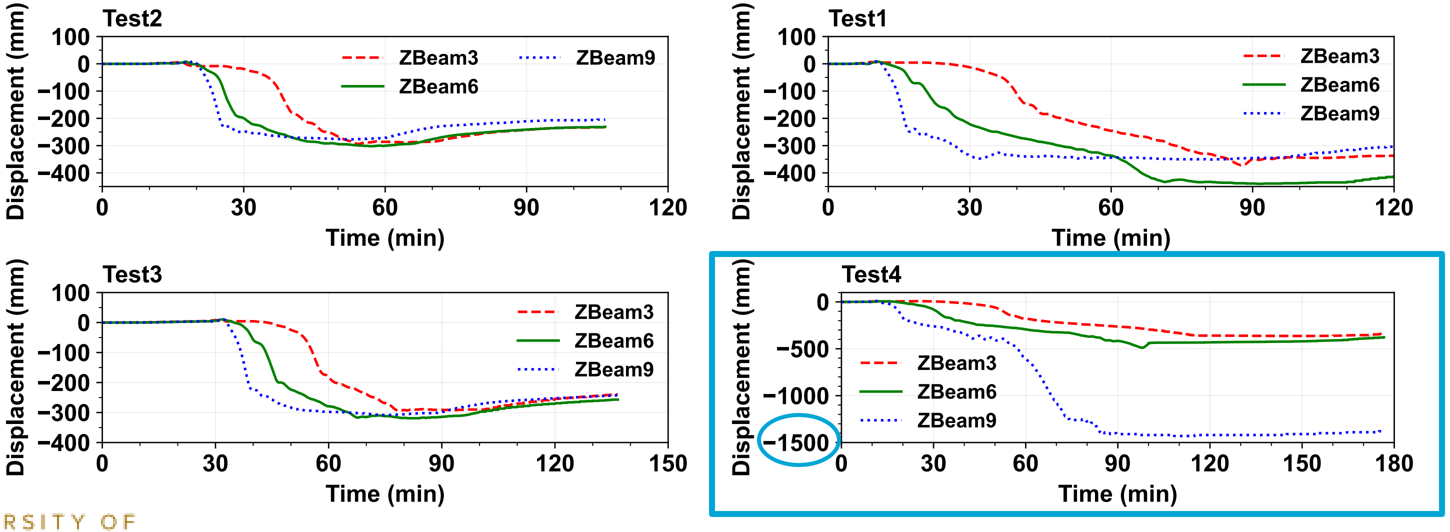
On structural fire responses

Structural fire response pattern

Fire developed rapidly towards the opening, causing structural elements in **BAY 3** (near the opening) to heat up first, leading to the **softening and bending** of steel members.

Due to **backward fire spread**, structural elements in **BAY 2 and BAY 1** heated up sequentially.

As **fuel load density (↑), longer burning duration (↑)** & **higher peak gas temperatures (↑),** resulting in **larger deflection (↑).**

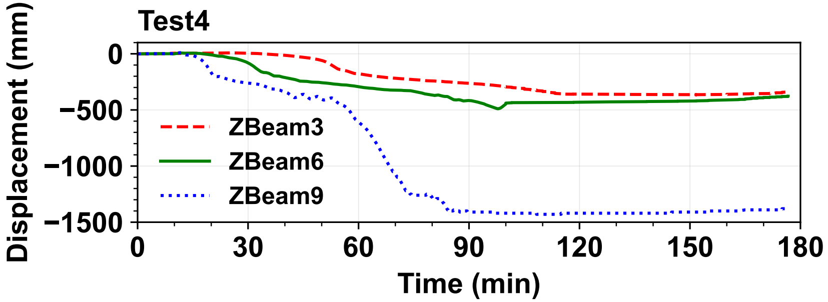


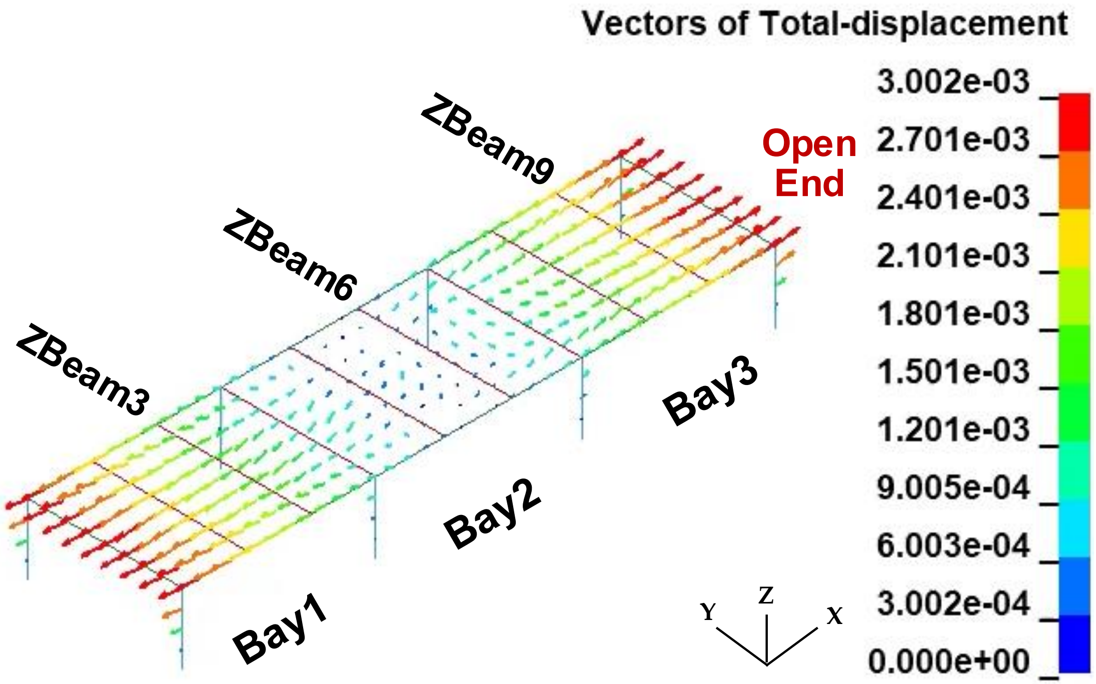
Effect of fuel load density

On structural fire responses

Structural fire response (Test 4)

Partial collapse in BAY3 (large deformation)





Compared to **Test 3**, the **fuel load density doubled** (from 20 kg/m^2 to 40 kg/m^2) in Test 4.

Compared to **Test 1**, the **opening size was reduced** to 1/2 in Test 4.

High fuel load and reduced ventilation together create severe localised heating, increasing structural collapse risk.

Conclusion

Effect of Ventilation:

- **Smaller openings → Longer fire duration → Larger deflections** due to extended heat exposure.
- **Test 6 (extremely small opening) → Oxygen-starved fire → Lower temperatures (<680°C) → Less non-uniform heating → Limited bending, and upward deformation in BAY 2.**

Effect of Fuel Load:

- **Higher fuel load → Longer burning, higher peak temperatures → larger deflections.**
- **Test 4 (high fuel load + reduced ventilation) → Prolonged localised heating → Increased collapse risk.**

🔥 Considering **ventilation, fuel load, and structural layout together is crucial** for identifying **worst-case scenarios** and preventing **fire-induced collapses**.

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Thank you.