Scientific Analysis and Validation of Hypothesis

Ir Prof. Richard YUEN

Three Dominant Modes of Fire Spread

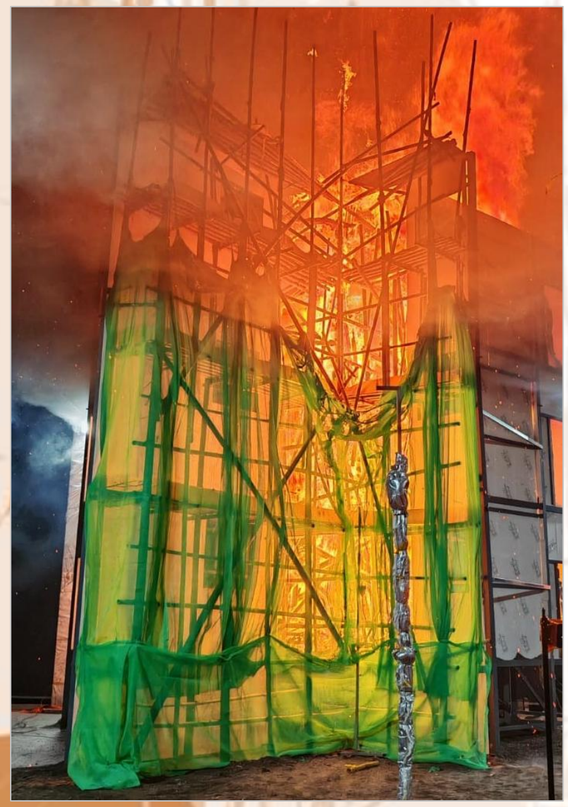
1. Rapid Vertical Fire Spread

2. Fire Spread into Units

3. Secondary Ignitions

Scientific Analysis

Full Scale Fire Test



Computational Fluid Dynamics (CFD) Simulation

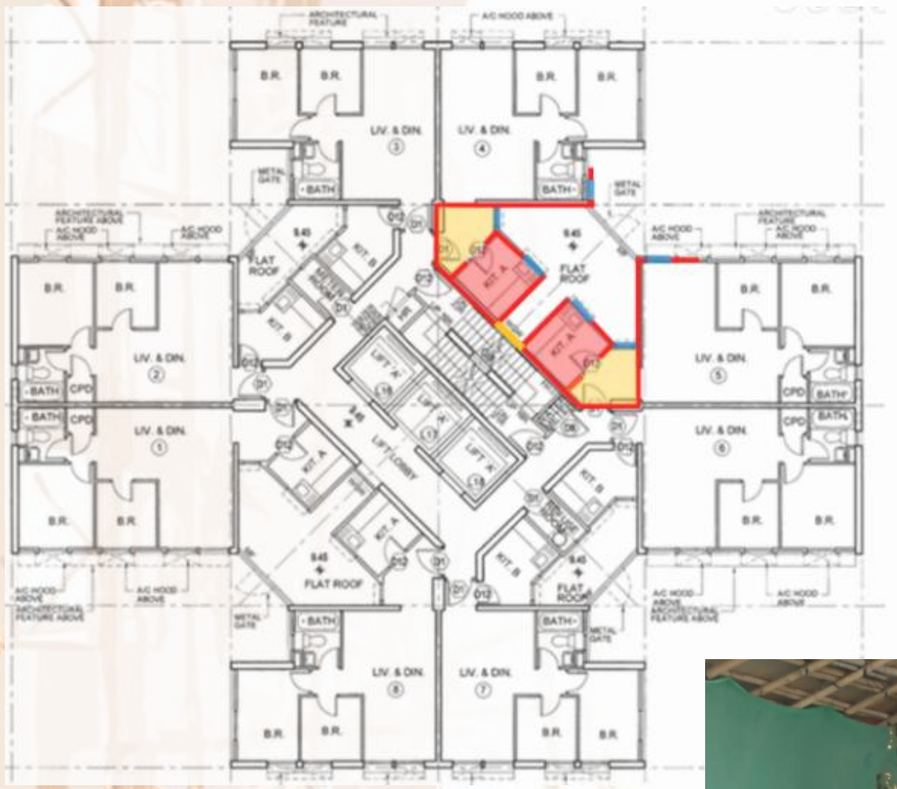
18 Key Observations

1. Fire Development
2. Polystyrene window covers
3. Safety nets and canvas
4. Staircase openings protection

Full Scale Fire Test – Test Arrangement

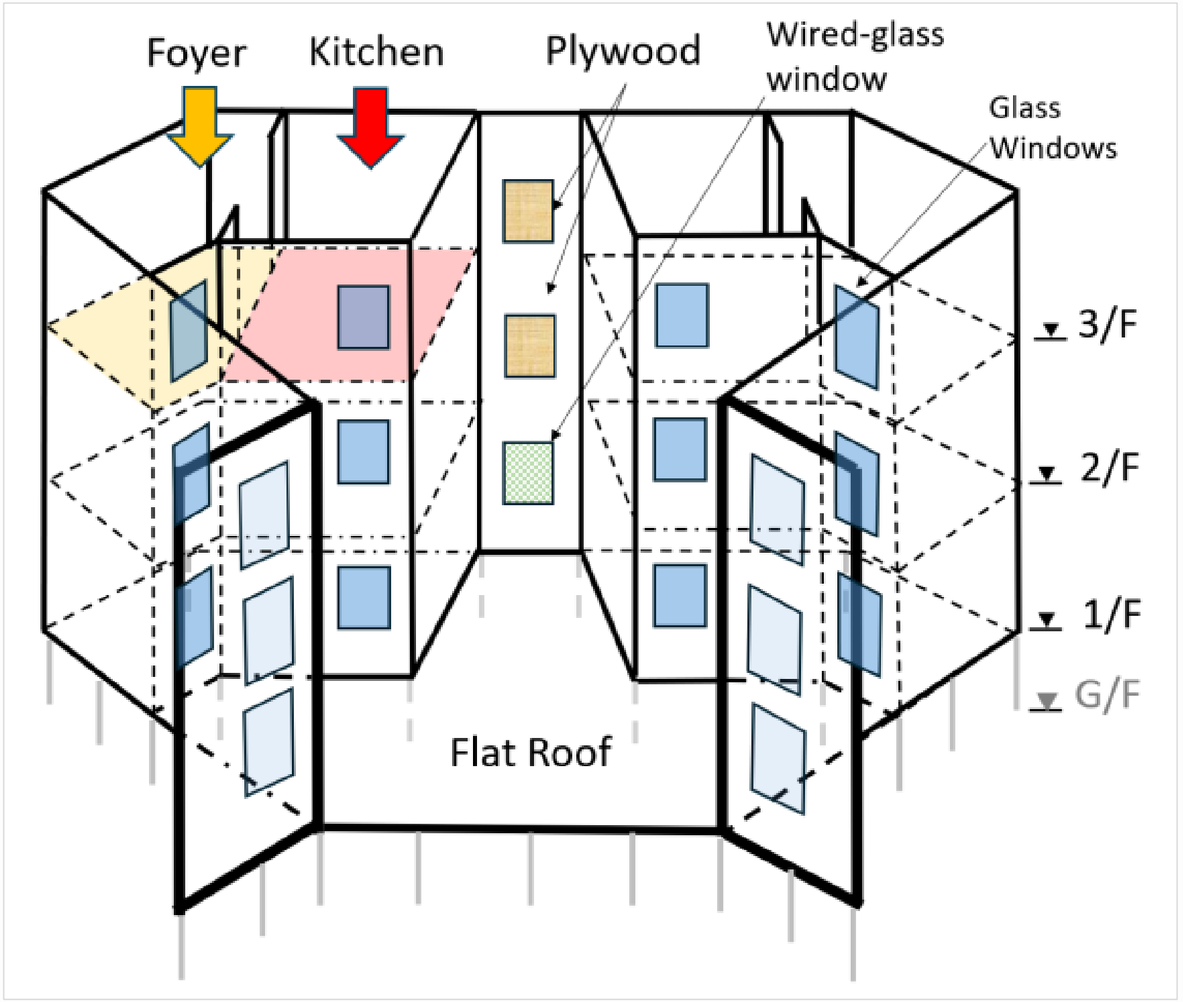
The Mega-Scale Cone Calorimeter
at Sichuan University of Science and Engineering (SUSE) 四川輕化工大學

Full Scale Fire Test – Test Arrangement



Wang Cheong House
Floor Plan

Discovery of Fire



Schematic of the Test Model

Full Scale Fire Test – Test Arrangement

Scaffolding Setup

External View With Safety Net

HRR Study of the Re-Entrant Configuration

Key Observations

Re-entrant configuration **increased**
- the peak HRR
- growth rate

Key Observation (4) of Appendix A-27

Fire Severity Analysis

Setup:

- 4-layers Scaffolding
- FR Safety Nets
- Wooden Planks
- Toe-boards
- Large Fire Source
- ✖ Polystyrene window covers

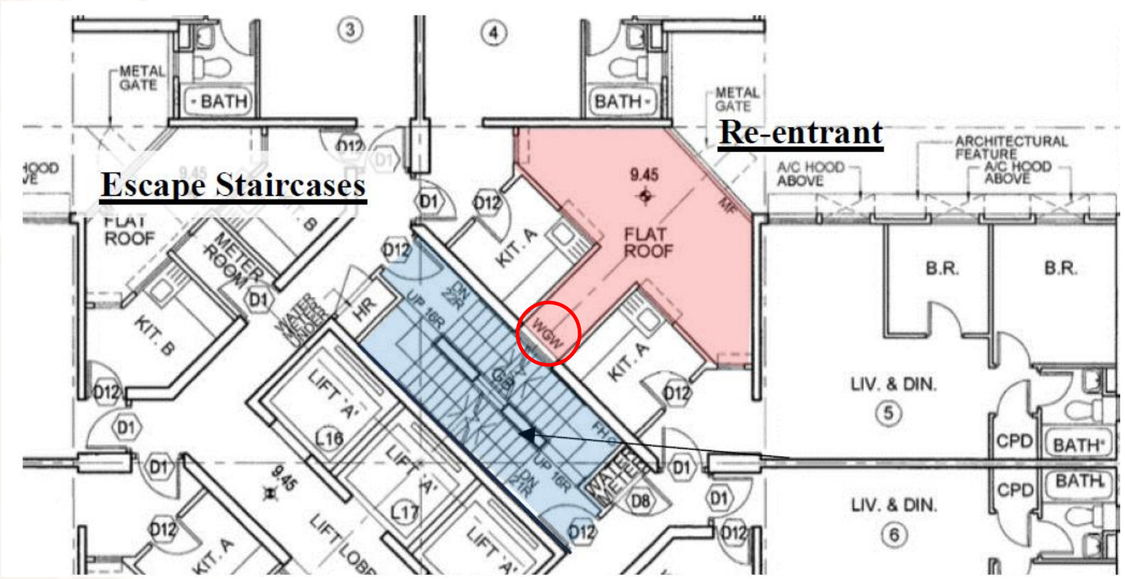
Fire Severity Analysis

Experiment Video

Fire Severity Analysis

Key Observations

- Fire and smoke infiltration through the gaps and holes in the wooden boards
- Movable boards were completely burned out.
- The use of staircase for evacuation impractical in the actual fire scene

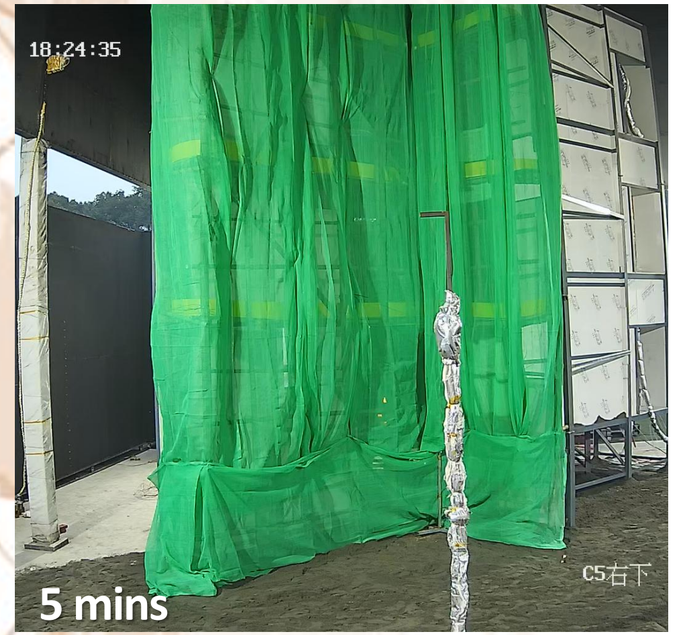


Key Observation (5) of Appendix A-27

Experiment Video

(30 mins from start of test)

Fire Severity Analysis



Key Observations

- Slow fire development during the first 30 min
- HRR increased dramatically in a few minutes and peaked at 29 MW.
- Associated rise in temperatures, from around 200°C to more than 1,000 °C.

Key Observations (6) and (7) of Appendix A-27

Fire Severity Analysis

Fire Severity Analysis	Time
3/F Kitchen and Foyer Windows Breaking Time	33 min 48 sec
2/F Kitchen and Foyer Windows Breaking Time	30 min 35 sec
1/F Kitchen and Foyer Windows Breaking Time	31 min 19 sec
Reaching Radiative Ignition Threshold at Kitchen Window	31 – 34 min
Reaching Radiative Ignition Threshold at Foyer Window	32 – 34 min

Key Observations:

- Both the foyer and kitchen window groups were exposed to extreme external heat fluxes, peaking at over 100 kW/m^2 at approximately 31 min and the foyer at about 33 min; the piloted or spontaneous ignition of combustibles is likely to occur.
- The breaking of the foyer and kitchen windows allowed fire and hot smoke to enter the premises from the building exterior; ignite combustible materials inside the premises.

Key Observations (8) and (9) of Appendix A-27

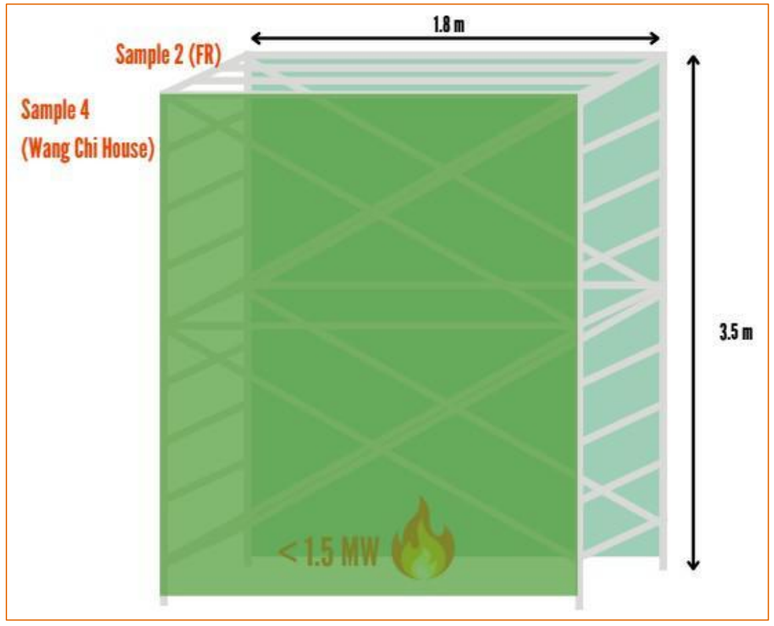
Comparison of Fire Behaviour of Safety Net Samples

Sample 1 (Uncertified) safety nets:
- without any accompanying certification

Sample 2 (FR) safety nets:
- conformed to both GB 5725-2009 and BS 5867-2:2008.

Sample 3 (non-FR) safety nets:
- Thermally deteriorated Sample 1
- non-compliant with both GB 5725-2009 and BS 5867-2:2008

Sample 4 (Wang Chi House) safety nets:
- Collected by the HKPF from Wang Chi House
  — building façades and
  — unused samples at ground level



Schematic of the Test Setup

Comparison of Fire Behaviour of Safety Net Samples

Experiment Video

Sample 2 (FR)

Sample 4 (Wang Chi)

Comparison of Fire Behaviour of Safety Net Samples

Sample 2 (FR)
(Partially Intact)

Sample 3 (Non-FR)
(Mostly Consumed)

Sample 4 (Wang Chi)
(Fully Consumed)

Key Observations

Sample 4 - Safety nets collected from Wang Chi House

- showed a faster spread than the Sample 2 (FR) and Sample 3 (non-FR) safety nets.
- all consumed in the test
- very likely lacking fire-retardant properties.

Key Observation (14 a) of Appendix A-27

Comparison of Fire Behaviour of Canva Samples

During the Test

After the Test

FR Canvas

Non-FR Canvas

FR Canvas
(Partially Intact)

Non-FR Canvas
(Mostly Consumed)

Key Observations

- non-FR canvas showed a faster fire spread than FR canvas.
- most of the non-FR canvas was consumed.
- The risk of fire spread along any location with the presence of non-FR canvas is increased.

Key Observation (14 b) of Appendix A-27

Full Scale Fire Test

Test	Fire Size (MW)	Safety Net	Polystyrene Covers	Canvas
1	Below 1.5	Sample 1 (Uncertified)	No	No
2	Below 1.5	Sample 2 (FR)	No	No
3	2.5	Sample 1 (Uncertified)	No	No
4	2.5	Sample 2 (FR)	No	No
5	2.5	Sample 1 (Uncertified)	Yes	No
6	2.5	Sample 2 (FR)	Yes	No
7	Below 1.5	Sample 3 (Non-FR)	No	No
8	2.5	Sample 3 (Non-FR)	No	No
9	2.5	Sample 4 (Wang Chi)	Yes	Non-FR
10	2.5	Sample 2 (FR)	Yes	FR
11	Below 1.5	Sample 2 (FR)	No	FR
12	Below 1.5	Sample 4 (Wang Chi)	No	FR
13	Below 1.5	Sample 4 (Wang Chi)	No	Non-FR

Fine-tuned Setup

Fire Spread Risks Associated with Polystyrene Window Covers

Key Observations

Polystyrene window covers

- promoted fire spread to other combustibles
- from literature, released toxic smoke

Key Observation (12) of Appendix A-27

Influence of FR Properties in Safety Nets and Canvas on Fire Development

Under Small Fire Conditions (HRR < 1.5 MW)

Key Observation

- FR safety nets significantly reduce the risk of ignition and fire propagation compared to uncertified and non-FR safety nets under small fire conditions.

Key Observation (1) of Appendix A-27

Influence of FR Properties in Safety Nets and Canvas on Fire Development

Under Small Fire Conditions (HRR < 1.5 MW)

Key Observations

- Bamboo remained unaffected
- Small fire spread along uncertified safety nets and non-FR safety nets
- Flaming droplets associated with the small fore propagation from the safety nets first ignited the nylon strips used for knotting, and then spread to the toe-boards and wooden planks

Key Observation (10) of Appendix A-27

Influence of FR Properties in Safety Nets and Canvas on Fire Development

Under Relatively Large Fire Conditions (HRR ~ 2.5 MW)

Key Observations

- Secondary ignition occur at a distance from the fire origin
- After the initial fire has burnt out, as uncertified and non-FR safety nets sustained ignition and allowed fire to spread.

Secondary Ignition Occurred in Test 8

Fire Spread to Other Construction Materials in Test 8

Key Observation (3) of Appendix A-27

Influence of FR Properties in Safety Nets and Canvas on Fire Development

Under Relatively Large Fire Conditions (HRR ~ 2.5 MW)

Key Observations

When compared with using FR safety nets, the use of non-FR safety nets demonstrated:

- Higher peak HRR
- Faster growth
- Higher associated temperature

Full Developed Fire in Test 4 using **FR Safety Nets**

Full Developed Fire in Test 8 using **non-FR Safety Nets**

Key Observation (11) of Appendix A-27

Influence of FR Properties in Safety Nets and Canvas on Fire Development

Under Relatively Large Fire Conditions (HRR ~ 2.5 MW)

Key Observation

Sufficiently large fire will consume all combustible materials within the re-entrant, irrespective of whether FR, non-FR or uncertified safety nets are used.

Post Fire Condition in Test 4 using **FR Safety Nets**

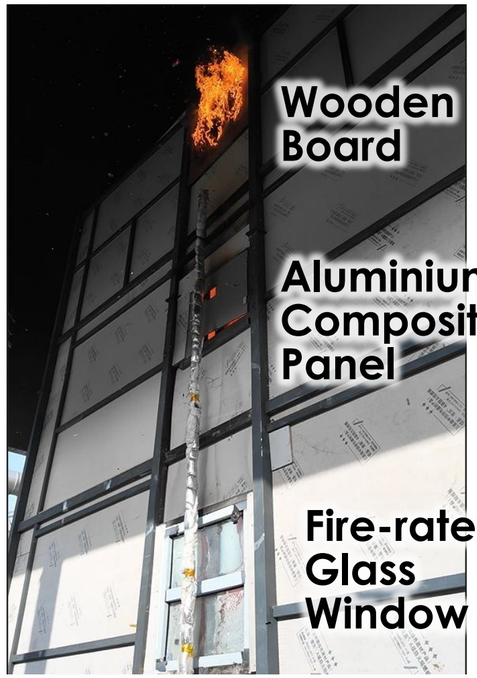
Post Fire Fire in Test 8 using **non-FR Safety Nets**

Key Observation (2) of Appendix A-27

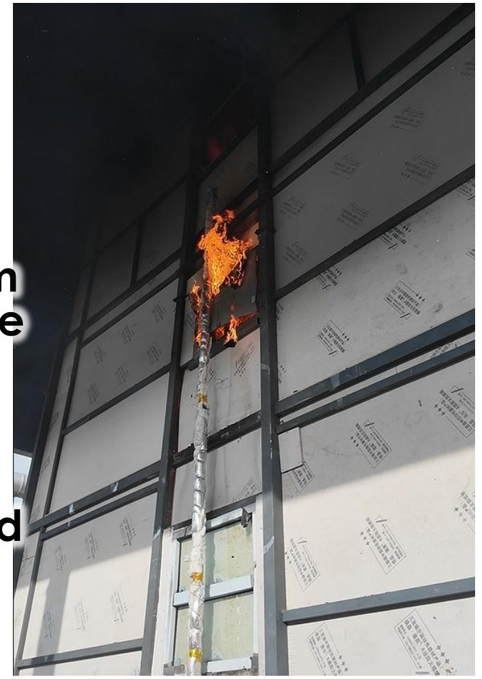
The Effectiveness of Opening Protection Materials

Test 9

Location	Material	Max Temp (Re-entrant Side)	Max Temp (Opened Side)
1/F	Fire-Rated Glass Window	1061 °C	56 °C
2/F	Aluminum Composite Panel	937 °C	605°C



Ignition of Wooden Board (4 min 40 sec)



Ignition of Aluminium Composite Panel (7 min 49 sec)

Post-Fire Condition

Key Observations

- Wooden board and aluminium composite panel are unsuitable for opening protection
- Fire-rated glass window remained intact and maintained lower temperatures, ensuring a safer environment for evacuation.

Key Observation (13) of Appendix A-27

Effectiveness of Opening Protection Materials

Test 13

Location	Material	Max Temp (Re-entrant Side)	Max Temp (Opened Side)
1/F	Fire-Rated Glass Window	1023 °C	30.8 °C
2/F	Fire-Rated Glass Window	709 °C	45.8°C

Key Observation

- The tests further reinforce that fire-rated glass windows effectively maintained significant temperature reductions and would have prevented the entry of smoke into staircases in the actual fire scene, ensuring safe evacuation remained a viable option.

Condition of Fire-rated Glass

Key Observation (17) of Appendix A-27

Secondary Ignition Behaviour

Secondary Ignition Persisting Time: range from **35 mins** to **2 hrs 47 mins**

Test	Secondary Ignition Persisting Time
1	2 hrs 13 min 10 sec
3	2 hrs 47 min 28 sec
5	2 hrs 02 min 52 sec
7	0 hrs 35 min 19 sec
8	1 hr 07 min 46 sec
9	1 hrs 05 min 16 sec
12	1 hr 53 min 50 sec
13	1 hr 38 min 37 sec

Test 1 [Sample 1 (Uncertified)]

Test 3 [Sample 1 (Uncertified)]

Test 5 [Sample 1 (Uncertified)]

Test 7 [Sample 3 (Non-FR)]

Test 8 [Sample 3 (Non-FR)]

Test 9 [Sample 4 (Wang Chi)]

Test 12 [Sample 4 (Wang Chi)]

Test 13 [Sample 4 (Wang Chi)]

Secondary Ignition Behaviour

Experiment Video

Formation of
Flaming Droplets

Secondary Ignition Behaviour and Time-to-Ignition Analysis

Procured Materials	TTI (s)
Uncertified Safety Nets (4 Layers)	46
Uncertified Safety Nets (2 Layers)	50
FR Safety Nets (4 Layers)	76
FR Safety Nets (2 Layers)	86
Non-FR Safety Nets (4 Layers)	48
Non-FR Safety Nets (2 Layers)	52
Toe-Board	42
Polystyrene Window Cover	31
Carton Box	11

Easily Ignitable Materials (TTI < 40 seconds)
Moderately Ignitable Materials (40 seconds ≤ TTI ≤ 75 seconds)
Delayed Ignitable Materials (TTI > 75 seconds)

Sample from Wang Yan House	TTI (s)
Toe-Board	19s (16s - 21s)
Nylon Strips	36s
Safety Nets (4 Layers)	44s (24s – 96s)
Safety Nets (2 Layers)	49s (27s – 78s)
Polystyrene Window Cover	60s
Wooden Plank	65s (58s – 79s)
Bamboo	112s (89s – 143s)

Sample from Wang Chi House	TTI (s)
Toe-Board	19s (18s -20s)
Safety Nets (4 Layers)	48s (30s -60s)
Safety Nets (2 Layers)	49s (27s - 72s)
Polystyrene Window Cover	67s
Bamboo	116s

Secondary Ignition Behaviour and Time-to-Ignition Analysis

Key Observation

- Small fires consistently propagated along the surface of non-FR safety nets, uncertified safety nets and safety nets collected from Wang Chi House, leading to the formation of flaming droplets
- As the small fires advanced and the flaming droplets dripped onto adjacent areas, igniting readily flammable materials such as nylon strips
- The ignition of these materials caused the fire to spread further to nearby combustibles, such as wooden planks and toe-boards

Key Observation (15) of Appendix A-27

Secondary Ignition Behaviour and Time-to-Ignition Analysis

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During the Test

After the Test

No Fire Spread
along Safety Nets
in Test 11

Fire Spread
along Safety Nets
in Test 12

Post-Fire Condition
in Test 11 using
FR Safety Nets and
FR Canvas

Post-Fire Condition
in Test 12 using
Safety Nets collected Wang Chi and **FR Canvas**

Secondary Ignition Behaviour and Time-to-Ignition Analysis

Fire Spread along Safety Nets in Test 13

Post-Fire Condition in Test 13
using **Safety Nets collected from Wang Chi House** and **non-FR Canvas**

Secondary Ignition Behaviour and Time-to-Ignition Analysis

Key Observations

- FR materials effectively reduce fire severity and limit fire spread
- Suspected non-FR materials, such as safety nets collected from Wang Chi House, promote fire spread through secondary ignition, involving more combustibles and increasing total heat release. However, the damage remains limited.
- The non-FR canvas accelerated the fire growth, transforming limited and localized fires into a widespread and intense blaze. The resulting excessive heat release was sufficient to ignite bamboo sticks, significantly increasing the HRR.

Key Observation (16) of Appendix A-27

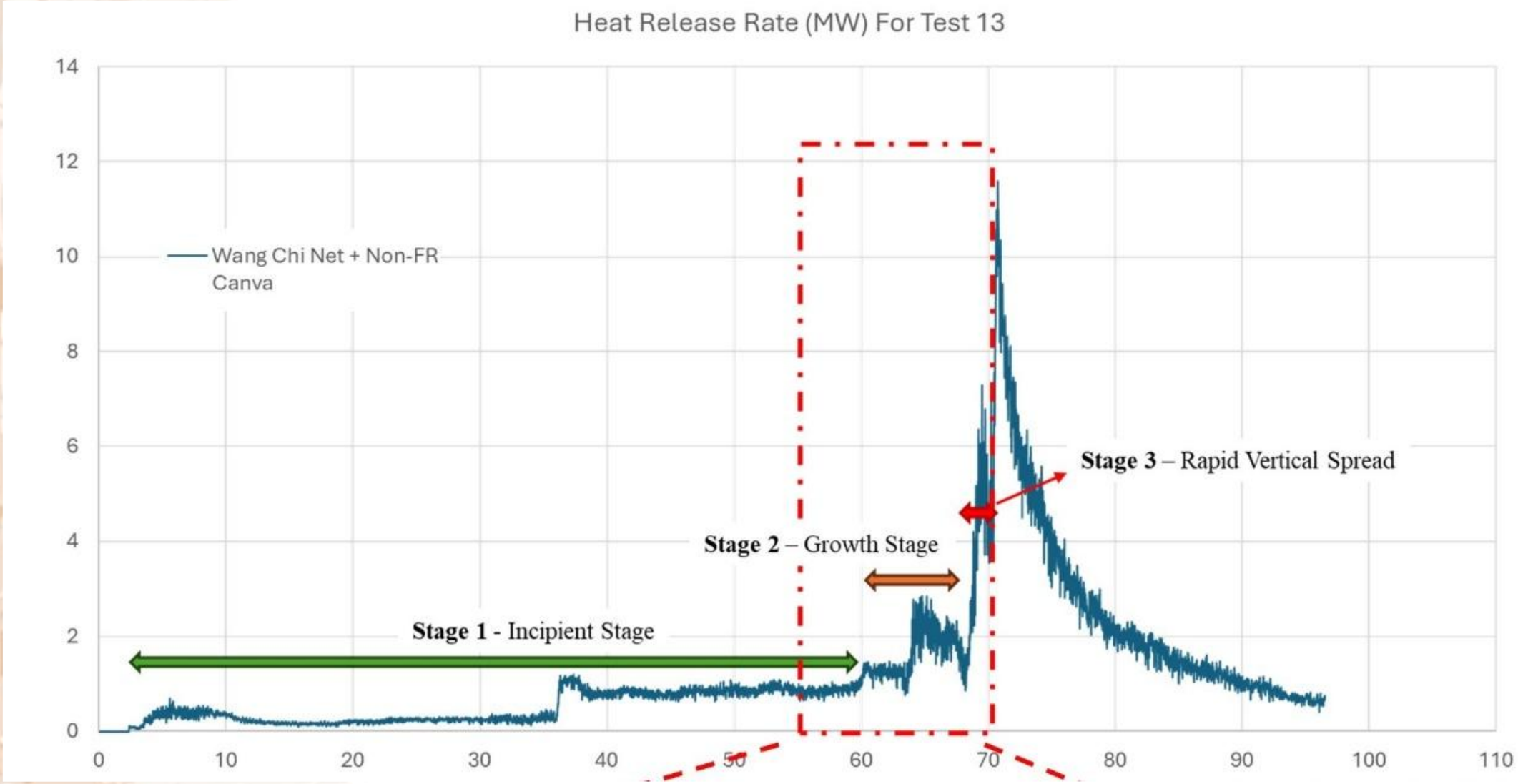
Correlation of Fire Test Findings with Fire Scene Conditions

Front View:
Re-entrant of Test 13

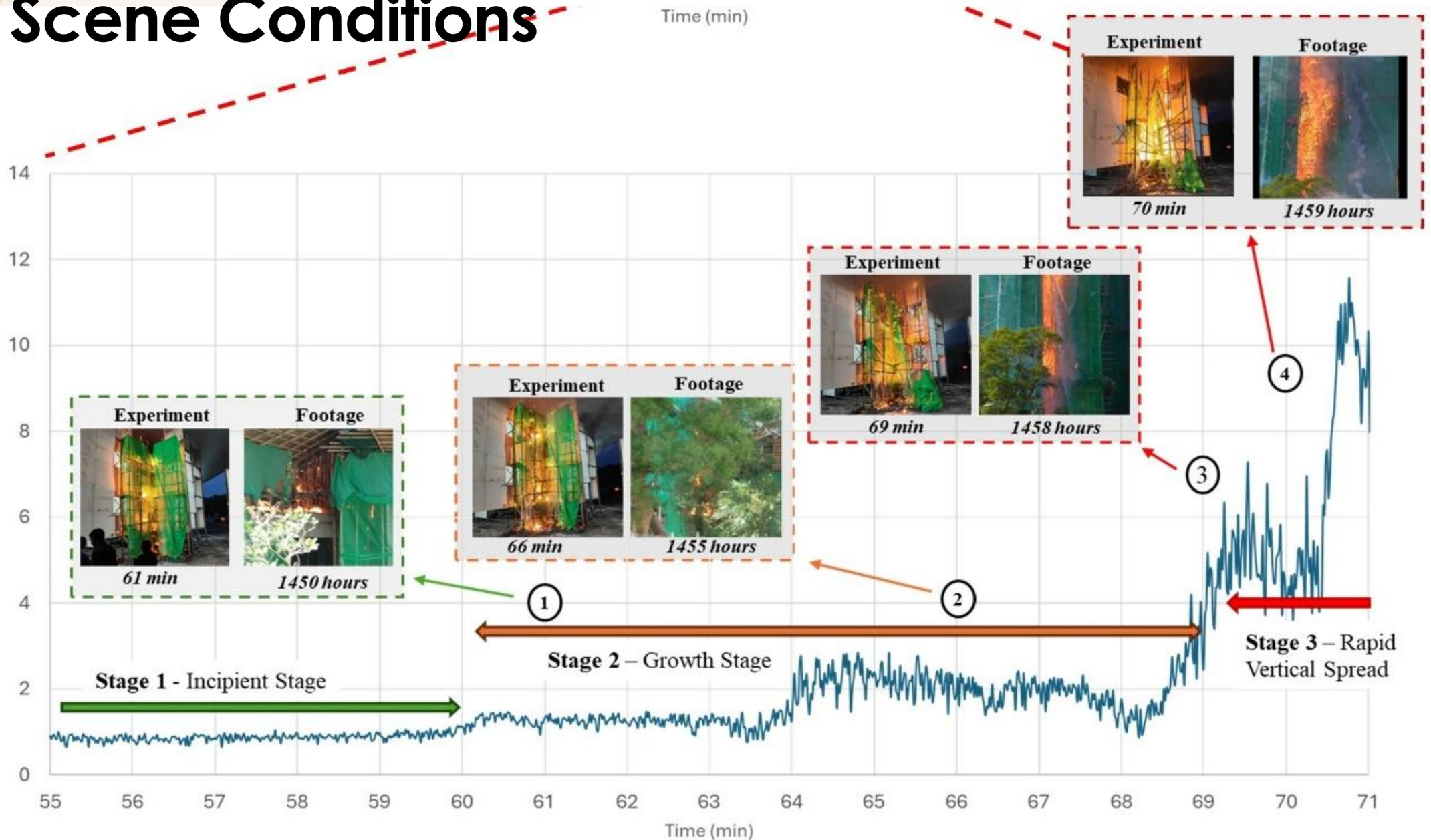
Front View:
Re-entrant of Wang Cheong House

Fire Size (MW)	Safety Net	Polystyrene Covers	Canvas
Below 1.5	Sample 4 (Wang Chi)	No	Non-FR

Correlation of Fire Test Findings with Fire Scene Conditions

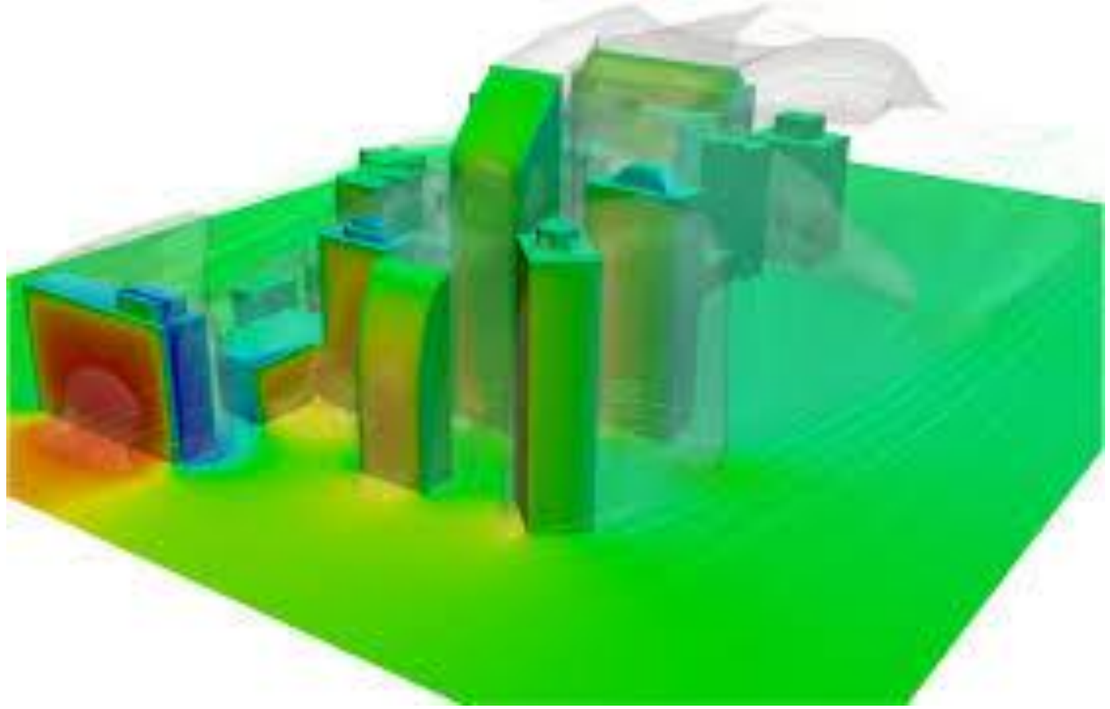


Correlation of Fire Test Findings with Fire Scene Conditions

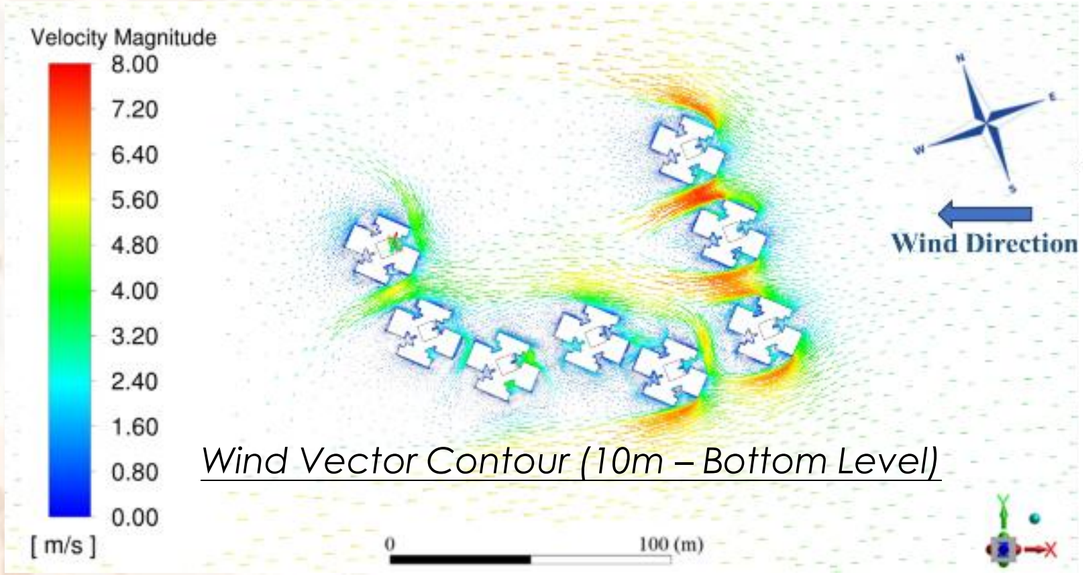


CFD SIMULATION

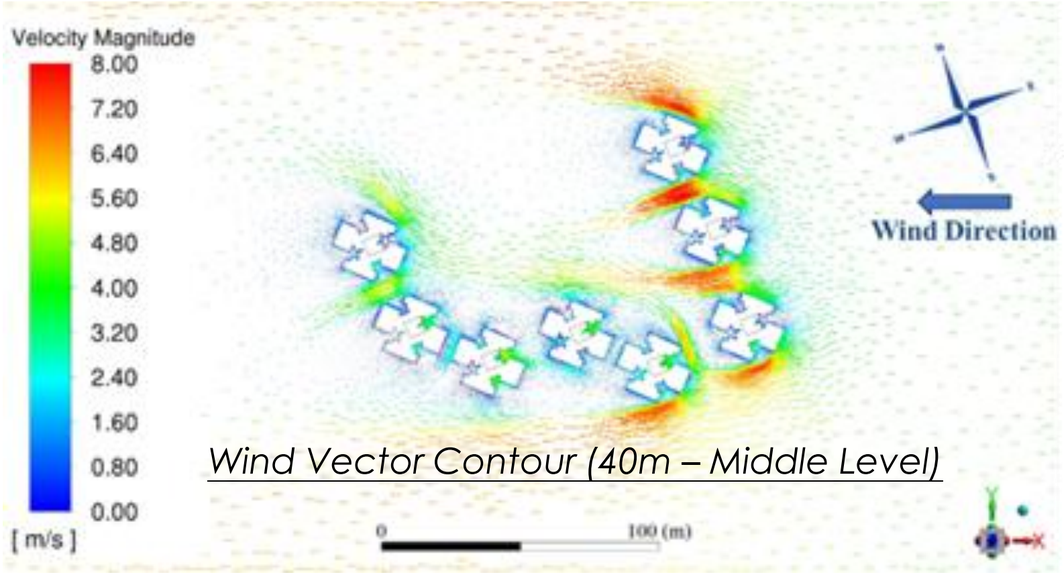
- Wind Profile
- Fire Dynamics Simulation
  - Results for Large Fire Size Cases
  - Results for Small Fire Size Cases



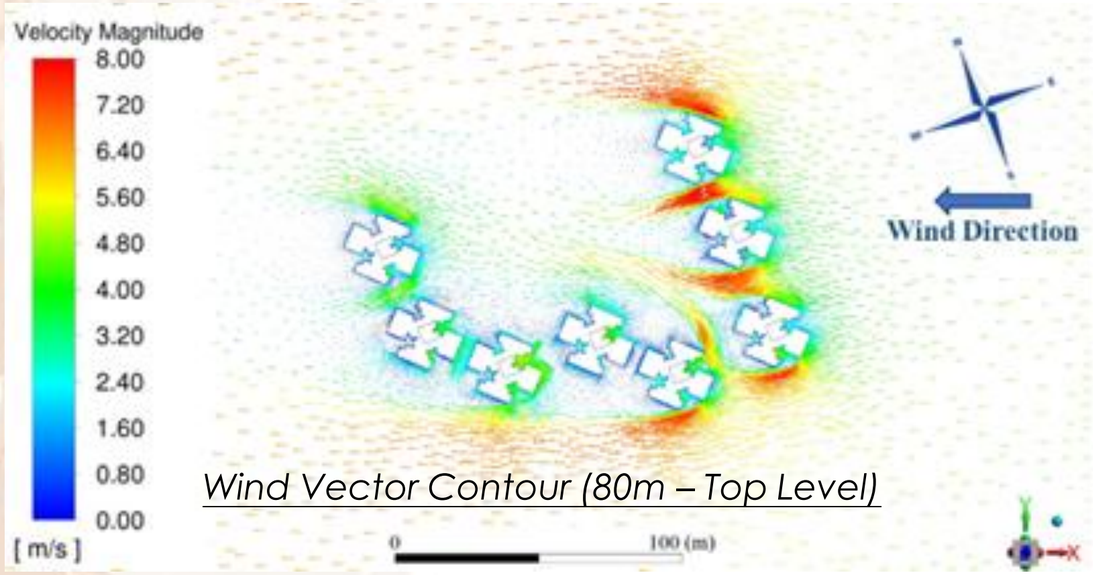
Wind Profile



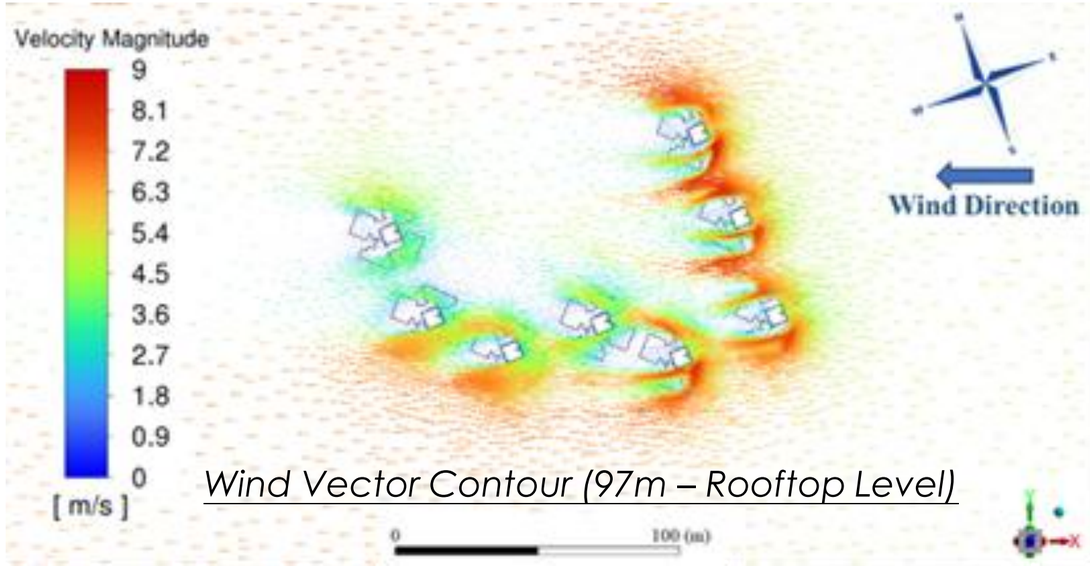
Wind Vector Contour (10m – Bottom Level)



Wind Vector Contour (40m – Middle Level)

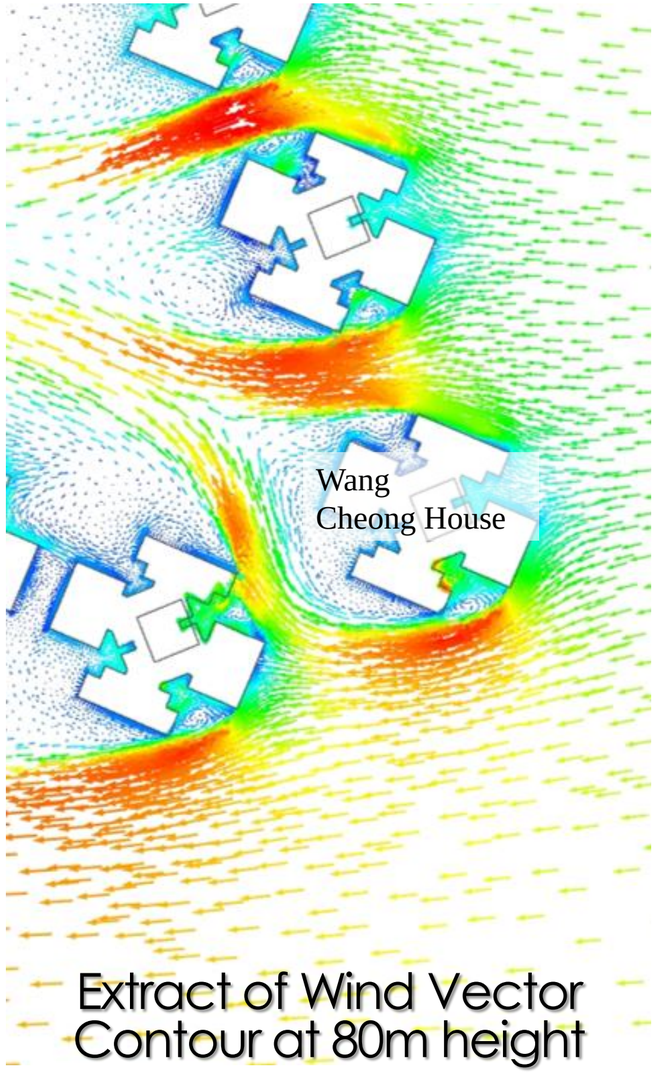


Wind Vector Contour (80m – Top Level)



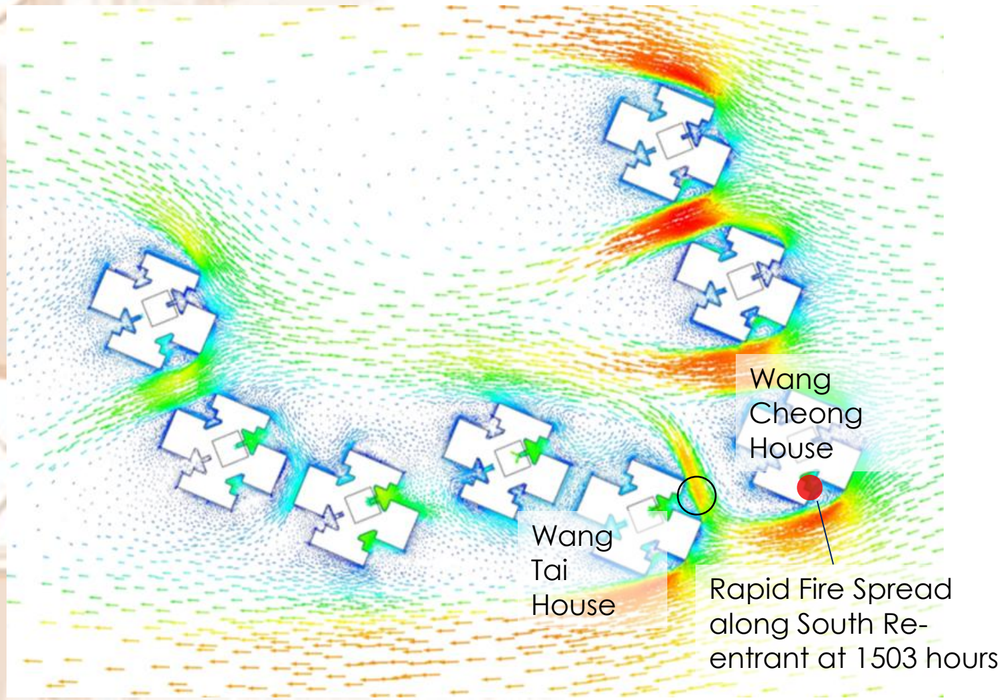
Wind Vector Contour (97m – Rooftop Level)

Wind Profile

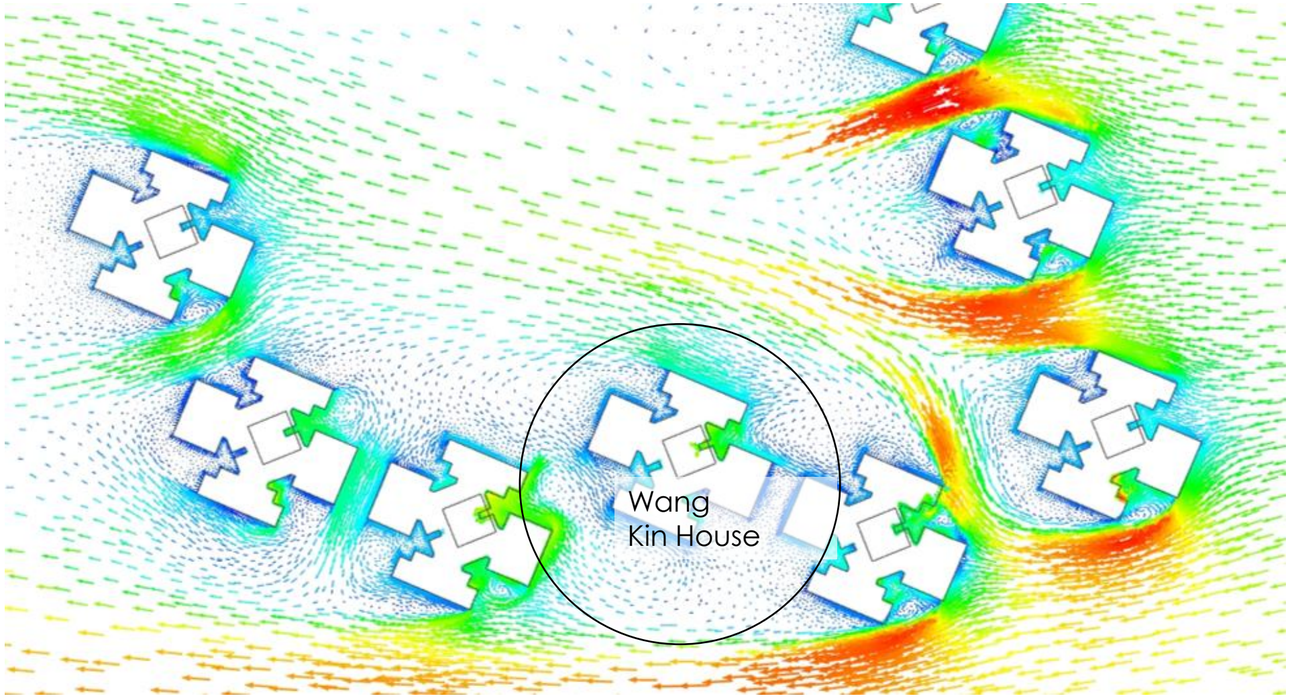


Extract of Wind Vector Contour at 80m height

Wind Profile



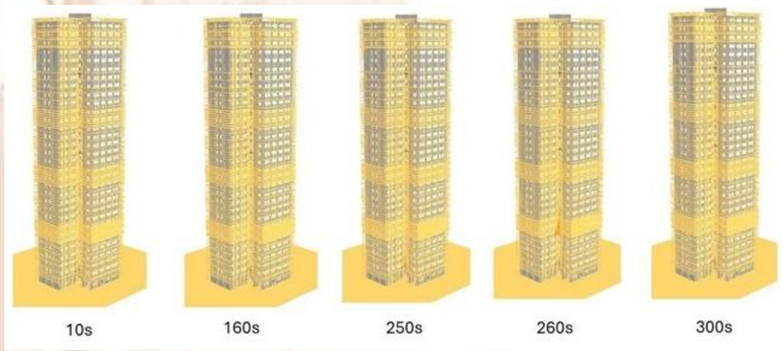
Extract of Wind Vector Contour at 40m Height



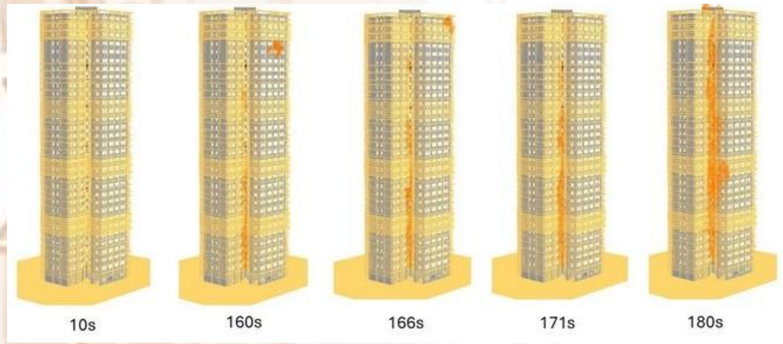
Extract of Wind Vector Contour at 80m Height

Fire Dynamics Simulation

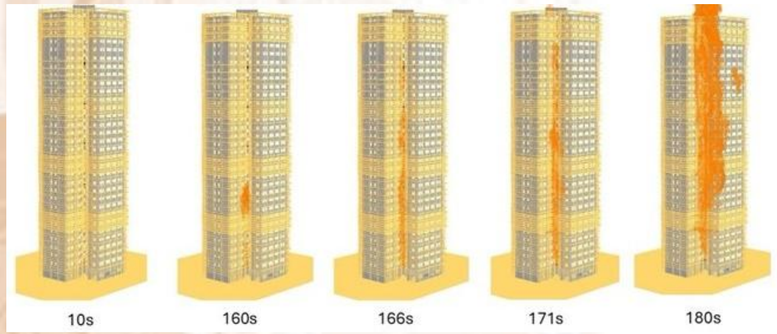
Small Fire Size Cases



Case 4



Case 5



Case 6

Key Observation (18) of Appendix A-27

Key Observations

- No rapid fire spread having occurred for FR safety nets (Case 4)
- The use of non-FR safety nets (Case 5) and Sample 4 safety nets from Wang Chi House (Case 6) resulted in significant fire spread and more severe fire development.

Case	Safety Net	Polystyrene Covers	Peak HRR (Time)	Time Fire Spread to		
				10/F	20/F	R/F
4	Sample 2 (FR)	No	30 MW (268 s)	-	-	-
5	Sample 3 (Non-FR)	No	747 MW (271 s)	158s	168s	178s
6	Sample 4 (Wang Chi)	No	795 MW (272 s)	160s	166s	171s

Validation of Hypothesis, Fire Development Fundamentals and Mechanisms

Modes of Fire Spread:

- Rapid vertical fire spread along the re-entrant,
- Secondary ignitions of the building's combustible envelope
- Fire spread into flats.

Rapid Vertical Fire Spread

- The blaze consumed the entire re-entrant and spread across 31 levels almost simultaneously
- The high density of materials, such as bamboo, toe-boards, wooden planks, safety nets, and nylon strips, provided a continuous fuel source at the re-entrant that sustained the fire
- The confined geometry of the re-entrants intensified the situation by restricting heat dissipation. This confinement led to the accumulation of heat, creating conditions favorable for the uncontrollable vertical fire spread

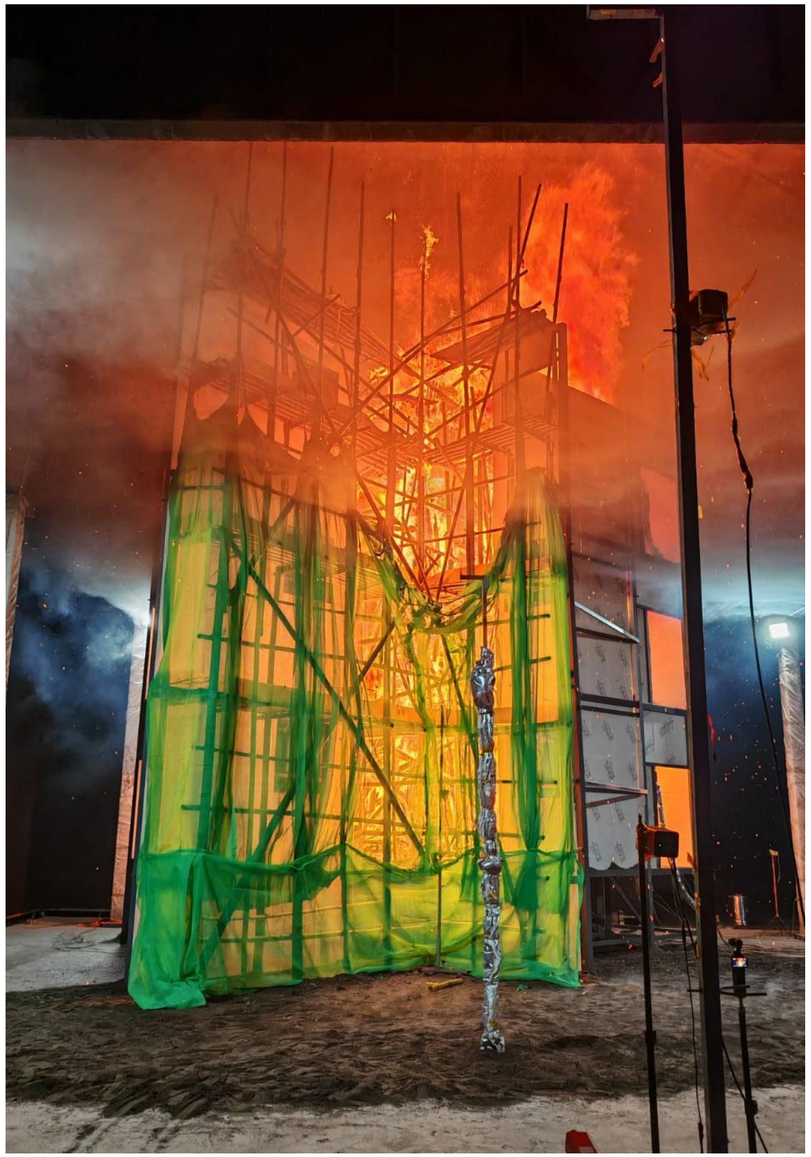
Rapid Vertical Fire Spread

Fire Severity From Identified Combustible Materials

- Fire Severity Analysis's results showed that, even with only the identified materials included (i.e. bamboo, safety nets, toe-boards and wooden planks), the fire exhibited extreme severity.

- The peak HRR reached 29 MW for a 3-storey setup, equivalent to the peak fire HRR of a bus or heavy goods vehicle in a tunnel fire.

- In a realistic scenario, with re-entrants spanning 31 storeys and containing additional combustibles (i.e. canvas, polystyrene window covers and backing papers of mosaic tiles), the fire severity could escalate dramatically



Rapid Vertical Fire Spread

Fire Dynamic in the Re-entrant Area

- Full-scale fire tests in Sichuan demonstrated that the development of rapid fire spread is highly sensitive to the size of the initial fire source.
- The rapid spread was primarily driven by the burning of a substantial amount of combustibles present in the re-entrant space, with the configuration of the re-entrant further amplifying the fire's intensity and spread.
- The abundant presence of combustible materials that played a crucial role in allowing the fire to grow in size, intensify and rapidly spread further to other combustibles within the re-entrant.

Rapid Vertical Fire Spread

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Roles of FR Properties in the Fire Spread

- Safety nets and canvas were found to play a significant role in the fire's development within the re-entrant.
- Not only were they combustible, but they were also interconnected to the large quantities of other combustibles in the re-entrant.
- Once ignited, they promoted fire spread to nearby combustibles, further accelerating the fire's growth.
- Therefore, the use of safety nets and canvas with FR properties is essential to effectively prevent the development and spread of fire.

Post-Fire Condition in Test 11 using FR Safety Nets and FR Canvas

Post-Fire Condition in Test 12 using Safety Nets collected Wang Chi House and FR Canvas

Rapid Vertical Fire Spread

Roles of FR Properties in the Fire Spread

The combination of **safety nets collected from Wang Chi House** and **non-FR canvas** resulted in rapid fire growth. This pairing of materials allowed small, localized fires to escalate into widespread and intense blazes

Fire Spread along Safety Nets in Test 13

Post-Fire Condition in Test 13
using Safety Nets collected from
Wang Chi House and non-FR Canvas

Rapid Vertical Fire Spread

Development of Rapid Fire Spread

Whether at the point of origin or during any of the other 11 occurrences of rapid fire spread in the re-entrant area, the fire consistently began on a small scale.

Two key factors drove its escalation:

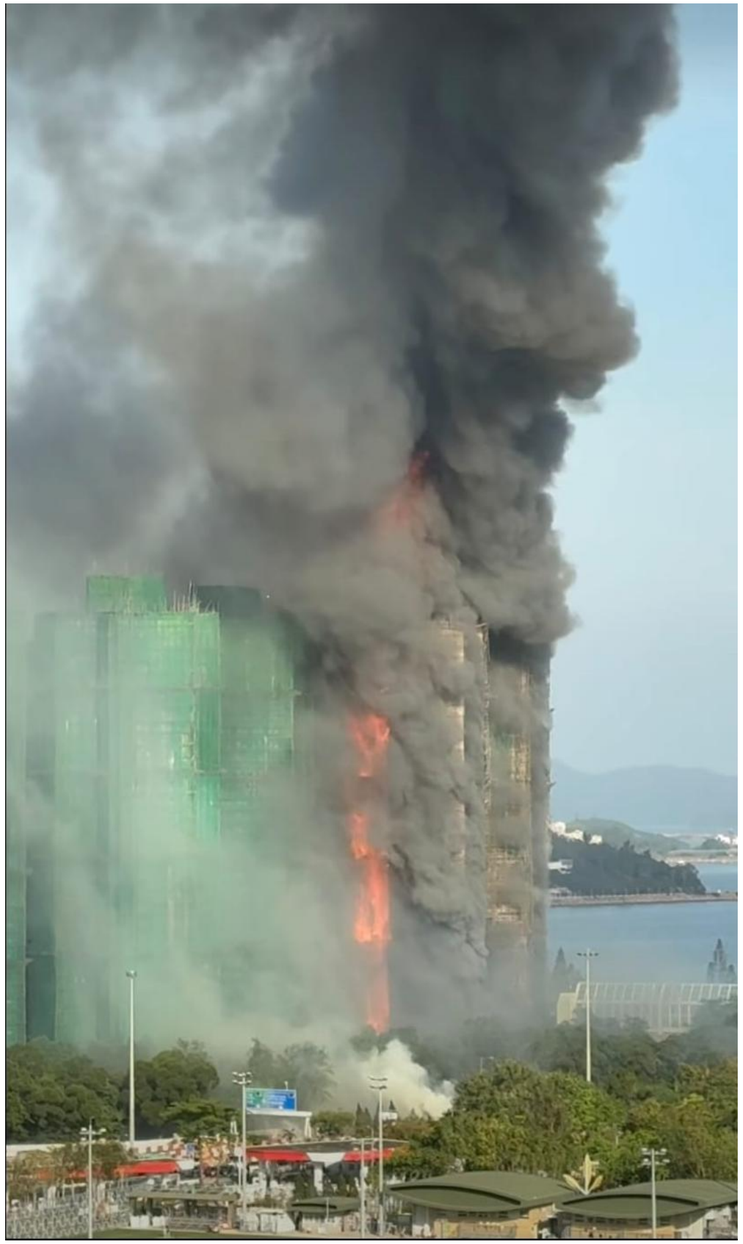
- The accumulation of combustible materials and
- The presence of suspected non-FR materials in the re-entrant space.

The build-up of combustibles provided a fuel source for fire development, while the non-FR materials facilitated fire growth and spread, ultimately allowing the fire to develop into a fully-fledged and rapidly spreading blaze.

Weather Conditions

Dry Weather

- Dry weather significantly reduces the moisture content in materials, making them more vulnerable to ignition.
- Combustible items dry out quickly in such conditions, lowering their ignition threshold.
- As a result, even small embers or flaming droplets can easily ignite these materials, enabling fire to spread rapidly.
- Dry conditions favor smouldering fires, as reduced moisture allows embers to persist and smoulder in materials for longer periods, potentially reigniting and sustaining the fire over time.



Weather Conditions

Windy Conditions

- Strong winds supply additional oxygen to the fire, intensifying its heat and accelerating its spread.
- The combination of dry and windy weather exacerbates conditions favorable for secondary ignition.
- Wind-carried embers and falling debris can travel long distances, igniting combustibles and enabling fires to develop quickly in new areas. Such weather conditions amplify the probability of uncontrollable fire spread, particularly in areas where abundant fuel sources are present.

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The End