Electronic Journal of Structural Engineering 16(1) 2016

Performance of modern building façades in fire: a comprehensive review

Kate TQ Nguyen, Pasindu Weerasinghe, Priyan Mendis, Tuan Ngo
Department of Infrastructure Engineering, University of Melbourne, VIC, Australia

Jonathan Barnett
Red Fire Engineers, Australia

Email: kate.nguyen@unimelb.edu.au, pthalpe@student.unimelb.edu.au

ABSTRACT: Building façades are considered as one of the critical elements of a buildings especially in case of fire where poor performance of façades lead to severe fire spread and building damage including human loss. There has been a significant improvement in façade design to ensure excellent building performance in terms of energy efficiency and requirements on aesthetic appeal. These changes fundamentally alter the behaviour of modern façades in fire and pose a risk to building safety and economic loss in the event of a fire. The latest incident at Grenfell tower demonstrated how vulnerable modern facades may be to fires, and emphasised how this vulnerability directly affects the safety of building occupants. The paper provides the first comprehensive review of current international design guidelines and test methods involving fire resistive design of facades. The influence of cladding material, geometry of the façade, cavities, wind and space between buildings are also discussed. Test methods that can be used to predict the flame and smoke spread are introduced and compared comprehensively. Critical aspects as the combustibility of the materials, and further studies on façade performance in fire are also highlighted.

Keywords: Façade, Fire, Buildings, Cladding, Safety Codes

1 INTRODUCTION

The facade is the skin of the building which keeps it separated from the external environment. With the current trend for the green building concept and sustainable construction, much focus is given on the energy efficiency of the façade. New energy efficient lightweight materials with good thermal insulation properties are being used to reduce the heat gain and loss through the façade. However, less attention is given to the behaviour of such facades in case of a fire. New façade designs have often resulted in significant changes to their fire behaviour and role in fire spread throughout a building. Facades can be a critical element in building fire spread; something designers must focus on.

Buildings with non-compliant facades pose a risk to occupant safety and may cause considerable economic loss in the event of a fire. The Grenfell Tower fire being the latest major incident, which occurred on the 14th of June 2017 and resulted in at least 80 fatalities. This tragedy demonstrated how vulnerable modern facades may be to fires and how this vulnerability directly affects the safety of building occupants. The installation of the façade system on the Grenfell Tower was completed in 2016; replacing the original, non-combustible facade. Therefore, an unprecedented opportunity exists to learn from the Grenfell Tower fire to avoid similar occurrences around the world.

At the moment, there is a lack of a critical review on how modern façades perform in fire and if current safety construction codes have adequately addressed these changes. This paper reviews the current design guidelines applicable to fire safety design of facades and provides direction where improvements are needed. It also discusses the various façade properties that influence fire behaviour while describing some of the prediction techniques used to model facade fire behaviour.

2 MAJOR FAÇADE FIRES

Table 2.1 summarises some recent façade fire incidents. In all cases, it was evident that there was a rapid fire spread along the exterior cladding due to the combustibility of the materials used. Combustible materials allow the flame to travel externally along the façades that cannot be extinguished by sprinklers and other active fire systems in buildings. The uncontrollable spread of fire through a façade has exposed buildings, especially high-rise structures with a large number of occupants, to a higher risk in a fire as it may limit egress routes and shorten the available evacuation time for occupants.

This has often resulted in authorities having jurisdiction strengthening guidelines to prevent such incidents from happening again in the future.

Table 2.1 A summary of recent major facade fire incidents

Building	Location	Year	Description	Damage
Jeffries Tower (18 stories) (Everett 2018)	Atlantic City, US	2018	Fire started at the mechanical room located in the 3rd floor which eventually spread throughout all 18 floors.	No injuries
10 storey hotel building (Cockburn 2017)	Rostov on Don, Russia	2017	The cladding on the building was made of 'very flammable material containing toxic elements' which increased the danger of rapid fire spread, according to government officials	2 dead
Grenfell Tower (Kirkpatrick et al. 2017) (24 stories)	London, UK	2017	Fire started at 4th floor and spread rapidly through the external cladding which consisted of ACM panels with PE core	79 dead 70 injured
Marco Polo Apartments (36 stories) (Farrer and Barney 2017)	Honolulu, US	2017	Fire started on the 26th floor and blaze rapidly spread higher. Influence of façade materials is still under investigation	3 dead 12 injured
The Address Downtown Dubai (302m tall) (Schreck and Gambrell 2016)	Dubai, UAE	2016	Fire started at the 20th floor during the new year's eve fire work display and spread rapidly through the ACP façade	14 minor injuries
Marina torch (352m) (Austin and Williams 2015)	Dubai, UAE	2015 & 2017	Fire initiated in the 52nd floor and spread quickly exacerbated by high winds	No injuries
16 Storey apartment building(Reuters 2015)	Baku, Azerbaijan	2015	Rapid fire spread along the cladding which were fitted after a renovation. 'Polyurethane panels' according to reports.	17 dead 60 injured
Tamweel Tower (160m tall) (Miers 2016)	Dubai, UAE	2012	A fire ignited which burned two separate broad vertical bands of exterior cladding from ground to roof level. ACM panels with PE core	Repair works have begun after 3 years
Saif Belhasa Building (13 stories) (Miers 2016)	Dubai, UAE	2012	Fire started at the 4th floor and spread rapidly to the roof level. Cladding consisted of ACM panels with PE core	9 flats destroyed 2 injured Debris damaged 5 vehicles
Lacrosse Building (Toscano and Spooner 2015)	Melbourne, Australia	2014	Fire started on the 6th floor and Fast-running flames soon ignited external wall cladding and aided by combustible material located within the wall structure quickly spread to the top of the building	No injuries
18 storey building(FPA 2012)	Roubaix, France	2012	Dramatic upwards spread of the fire from its origin to the top of the 18-floor building, apparently fuelled by its highly flammable outer cladding	1 dead 6 injured
28 storey building (Barboza 2010)	Shanghai, China	2010	Building was undergoing renovations which involved installing energy saving insulation. Fire was believed to have spread on polyurethane insulation to external walls	53 dead 90 injured
Monte Carlo Hotel (32 stories) (Duval 2008)	Las Vegas, US	2008	Fire was burning along the combustible components of the building's architectural trim and the exterior insulation and finish system which consists of a layer of expanded polystyrene foam adhered to gypsum sheathing	13 minor injuries

Following the Pre-2012 incidents in the UAE their fire code provisions for exterior cladding fire safety were modified. Stricter guidelines were introduced and separate annexes were added with the intention to exclude the insulation and cladding materials most prone to external fire spread; using mandatory requirements rather than giving informative advice (Miers 2016).

Similar events unveiled after the Lacrosse tower fire (2014) in Melbourne. A post incident analysis undertaken by the Melbourne Metropolitan Fire Brigade has identified the external wall was not non-combustible contrary to the prescriptive requirements of the National Construction Code (NCC), Australia. Later an audit conducted by the Victorian Building Authority (VBA) found that the NCC requirements for external walls, including the suitability of materials, are inconsistently applied and poorly understood (Victorian Building Authority 2016). This has triggered a review of the NCC including the Codemark building product certification scheme which is often used to assess the compliance of building products. After the incident, Standards Australia published a new Australian Standard (AS 5113-2016) (Standards Australia 2016) on “Fire propagation testing and classification of external walls of buildings”, that provides procedures for the fire propagation testing and classification of external walls of buildings according to their tendency to limit the spread of fire via the external wall and between adjacent buildings. This standard was developed based on international practice and is generally consistent with the testing criteria prescribed in ISO 13785.2 (International Organization for Standarization 2002) and similar to BS 8414 (British Standard Institute 2015) Parts 1 and 2. A detailed review of different international building codes regarding façade fire design is presented in Section 3.

Investigations carried out after these fire incidents raised a common issue. Combustible material present in façade cladding is the main contributor for rapid spread of fire. More often it was a Polyethylene (PE) core, sandwiched between Aluminium panels used as the exterior cladding which is the problem.

Another common issue is that some of these buildings were renovated before the fire disaster and the cladding which was installed during the renovation was the main cause of fire spread. Although new rules and regulations are put forward after a catastrophic event, typically those apply only to new constructions which take place after the rules are announced. The vulnerability of existing buildings is usually not altered. Such buildings could be in a much worse condition as they were constructed long before fire design guidelines were introduced coupled with potential issues of improper building maintenance.

3 COMPARISON OF BUILDING CODE REQUIREMENTS FOR FIRE RESISTIVE DESIGN OF FACADES

3.1 *National Construction Code Australia*

The National Construction Code (NCC) Australia expects a certain performance criteria to be satisfied by the external cladding of a building (The Australian Building Codes Board 2016 (b)). There are two pathways to meet the specified performance criteria; a deemed-to-satisfy solution (DtS) or a performance solution. Where a DtS solution is proposed, the relevant performance requirements (CP1 to CP9) are assumed to be satisfied. Where a performance solution is proposed, it requires a report from a qualified fire engineer. The report is often based on full-scale façade tests carried out in accordance with BS 8414 (British Standard Institute 2015), ISO 13785 (International Organization for Standarization 2002), NFPA 285 (National fire protection association 2012), or any equivalent international standard. Standards Australia has recently released AS 5113 (Standards Australia 2016), a full-scale façade test based on BS 8414 and ISO 13785. However, it is not yet referenced in the NCC (although this will soon change with the release of NCC 2016 Amendment 1(The Australian Building Codes Board 2018).

Among the performance criteria specified by the NCC, CP2 is important regarding fire safety of facades as it emphasises that external walls (including cladding products) must not contribute to the spread of fire in a building and between buildings (The Australian Building Codes Board 2016 (b)). Depending on the nature of the façade, the cladding or a part of the cladding may be evaluated as a part of the external wall or as an attachment to the wall, which has different safety requirements.

When the cladding is part of the external wall, The DtS requirement is that it must be non-combustible for most Type A or Type B buildings (Specification C1.1 clause 3.1 (b) and 4.1 (b)) (The Australian Building Codes Board 2016 (b)). The construction types (there are three, Types A, B or C) are a DtS requirement based on the use of the building and its size. Determining a material’s combustibility for purposes of this clause is done by testing in accordance with AS 1530.1 (Standards Australia 1994). For laminated products, the test is carried out for each individual layer. The NCC prescribes the non-combustible requirements for bonded laminated elements as follows (Specification C1.12(f)) (The Australian Building Codes Board 2016 (b)) :

- Each laminate is non-combustible in accordance with AS 1530.1 (Standards Australia 1994)
- Each adhesive layer does not exceed 1 mm in thickness; and
- The total thickness of the adhesive layers does not exceed 2 mm; and
- The Spread-of-Flame Index and the Smoke-Developed Index of the laminated material as a whole does not exceed 0 and 3 respectively in accordance with AS 1530.3 (Standards Australia 1999)

However if one or more layers (excluding the adhesives) are combustible (as determined accordance with AS 1530.1), it violates the non-combustibility requirements and therefore cannot be used as part of a DtS solution where a non-combustible material is required in façade (Australian Building Codes Board 2016 (a)).

In addition to external claddings, other elements such as framing, spandrels, insulation and internal lining (e.g. plasterboard) are evaluated as part of an external wall. The external wall can be load bearing or non-load bearing. The NCC defines load bearing as carrying a gravity load other than a wall's own weight. Depending on the load bearing condition and the distance from the fire source, the NCC also specifies a fire resistance level (FRL) in minutes for the three main performance criteria; structural adequacy, integrity and insulation (Specification C1.1 clause 3.1 (a)) (The Australian Building Codes Board 2016 (b)) (see Table 3.1). The FRL is not related to time of performance in a real fire, but time to failure in a test furnace. These times are not related.

When cladding is considered by the NCC to be an attachment to an external wall, combustible materials can be used, as long as it does not impair the external wall's fire-resistance (Specification C1.1 clause 2.4) (The Australian Building Codes Board 2016 (b)). The material must also meet the fire hazard properties prescribed in specification C1.10 which specifies a group number, smoke growth rate index or average specific extinction area determined in accordance with AS 5637.1. Furthermore, the combustible cladding must not be located near or directly above an exit which might be impaired by a cladding fire and it must not constitute an undue risk of fire spread via the façade of the building. The attachment should also meet the required FRL for that construction type (refer to Table 3.1).

However, the NCC also specifies exceptions for combustible materials or materials containing combustible components (Specification C1.12) (Australian Building Codes Board 2016 (a); The Australian Building Codes Board 2016 (b)). These exclusions include plasterboard, perforated gypsum lath with a normal paper finish, fibrous-plaster sheet, fibre-reinforced cement sheeting and pre-finished metal sheeting having a combustible surface finish not exceeding 1 mm thickness and where the Spread-of-Flame Index of the product is not greater than 0.

Table 3.1 Type A Construction: FRL of building elements (The Australian Building Codes Board 2016)

Building element	Class of building – FRL: (in minutes) Structural adequacy/Integrity/Insulation			
	2,3 or 4 part	5,7a or 9	6	7b or 8
EXTERNAL WALL (including any column and other building element incorporated therein) or other external building element, where the distance from any fire-source feature to which it is exposed is—				
For loadbearing parts-				
Less than 1.5m	90/ 90/ 90	120/120/ 120	180/180/ 180	240/240/ 240
1.5m to less than 3m	90/ 60/ 60	120/ 90/ 90	180/180/ 120	240/240/ 180
3m or more	90/60/30	120/60/ 30	180/120/ 90	240/180/ 90
For non-loadbearing parts-				
Less than 1.5m	-/ 90/ 90	- /120/120	- /180/180	- /240/240
1.5m to less than 3m	-/ 60/ 60	-/ 90/ 90	- /180/120	- /240/180
3m or more	-/-/-	-/-/-	-/-/-	-/-/-

3.2 *Approved Document B - UK*

Approved Document B (ADB) (Department of Communities and Local Government 2010) is used as the guideline under building regulations to determine fire safety. Similar to the NCC, fire spread must be limited within the building, over the external surface of the building and from one building to another. While ADB specifies certain conditions to be satisfied for the cladding to be classified as fire resistive, it also provides an alternate means of compliance by testing to BS 8414 (British Standard Institute 2015) and assessment in accordance with BR 135 (Centre for Window and Cladding Technology 2017). When the wall itself is required to resist fire, it must be in compliance with EN 1364-4 (European Committee for Standarization 2014). As this paper is focused on façade fires, the guidelines that applies primarily to facades will be discussed in detail.

There are sets of perspective rules governing façades. If a building contains a floor more than 18 m above ground level, the following conditions apply (Department of Communities and Local Government 2010).

- Any insulation product, filler material (not including gaskets, sealants and similar) etc. used in the external wall construction should be of limited combustibility and meet the requirement of Euroclass A2 materials;
- External surface above 18m should be Class B;
- External surface below 18 m can be Class C provided distance from boundary exceeds 1m.

Combustibility of materials are classified in accordance with EN 13501-1 (European Committee for Standarization 2009) as A1, A2, B, C, D, E and F. A1 has the highest performance and F the lowest. Table 3.2 shows the respective classes and their combustibility

Table 3.2 Combustibility class of materials used in ADB (Centre for Window and Cladding Technology 2017; Department of Communities and Local Government 2010)

Class	Definition
A1	Non – combustible. (As defined in ADB Table A6)
A2	Limited combustibility. (As defined in ADB Table A7)
B	FIGRA ≤ 120 W/s and LFS < edge of specimen and THR_{600s} ≤ 7,5 MJ
C	FIGRA ≤ 250 W/s and LFS < edge of specimen and THR_{600s} ≤ 15 MJ

FIGRA - fire growth rate index, LFS - lateral flame spread (m), THR_{600s} - total heat release within 600 s

According to guidelines (Centre for Window and Cladding Technology 2017; Department of Communities and Local Government 2010), if the building does not contain a floor more than 18 m above ground and the façade is within 1 m of the boundary, the external surface must comply with Class B construction. When the façade is more than 1 m from the boundary for buildings more than one storey and shorter than 18 m, Class C material can be used for the external surface. In all cases, if the façade contains cavities, cavity barriers must be provided in accordance with section 9. Thin membranes for water proofing, air tightness and vapour control are excluded from the requirements provided that they do not increase the risk of fire spread by causing other materials to ignite. Paint finishes can also be excluded but they need to comply with the requirements for surface spread of fire (i.e. class B and class C depending on the height).

Three other options are allowed as alternative methods, which are further discussed in the technical guide note 18 by the Centre for window and cladding technology (Building Control Alliance 2015). These clarifications should be prepared by a qualified fire engineer to ensure the building performance will be equivalent to the requirements from ADB. The alternative solutions also take into account several façade characteristics such as geometry and factors restricting fire spread which are not found in the NCC requirements.

3.3 *International Building Code - US*

The US adopts the International Building Code (IBC) (International Code Council 2012) as the model document to form building regulations governing different states. Although there are some variations across the states, the base provisions are the same. Similar to the NCC in Australia and the ADB in the UK, the IBC has two avenues to demonstrate if a façade is adequately fire resistive. Either the façade should comply with the material and fire resistance rating specified by the code depending on the construction type or the façade assembly must pass test NFPA 285 (National fire protection association 2012) – *Standard fire test method for evaluation of fire propagation characteristics of exterior non-load bearing wall assemblies containing combustible components*.

The following construction types are defined in the IBC depending on the combustibility of the material used in building components (International Code Council 2012). The fire-resistance rating requirement varies for different construction types as shown in Table 3.3.

- Type I and II – Building elements listed in Table 601 (Primary structural frame; exterior and interior bearing walls, non-bearing walls and partitions; floor and roof) are of non-combustible material, except as permitted in section 603 and elsewhere in the IBC
- Type III – Exterior walls are of non-combustible material and the interior are of any material permitted by the IBC

- Type IV (Heavy Timber, HT) – Exterior walls are of non-combustible material and the interior building elements are of solid or laminated wood without concealed spaces
- Type V - Structural elements, exterior walls and interior walls are of any materials permitted by the UBC

Depending on the fire separation distance and occupancy level, the following fire safety requirements are specified for non-load bearing cladding on different construction types (International Code Council 2012) (See Table 3.3). When fire separation distance is more than 9.2 m (30 feet) there is no requirement on the façade's fire rating. The occupancy level is determined depending on the use of the building such as assembly (A), business (B), educational (E), factory and industrial (F & I), mercantile (M), storage (S), High-hazard (H) and so on.

The combustible materials that are permitted have the following limitations (International Code Council 2012);

- Combustible wall covering should not exceed 10 % of the exterior wall surface area where the fire separation distance is 1.5m (5 feet) or less
- Combustible exterior wall coverings shall be limited to 12.2 m (40 feet) in height above grade plane
- The area of a combustible wall is limited in order to reduce the spread of severe external fire spread. The threshold of 12.2 m (40 feet) from the the grade plane for a combustible exterior wall is related to fire brigade accessibility.

In terms of material combustibility, the classification in the IBC is similar to the NCC in Australia where there is no category for materials with limited combustibility, but only combustible and non-combustible groups.

Table 3.3 Fire-resistance rating requirement for exterior walls based on fire separation distance (International Code Council 2012)

Fire separation distance = X (feet)	Type of construction	FRR in hours		
		Occupancy group H	Occupancy group F-1, M, S-1	Occupancy group A, B, E, F-2, I, R, S-2, U
$X < 5$	All	3	2	1
$5 \leq X < 10$	IA	3	2	1
	Others	2	1	1
$10 \leq X < 30$	IA, IB	2	1	1
	IIB, VB	1	0	0
	Others	1	1	1
$X \geq 30$	All	0	0	0

The IBC also relaxes the limits for a combustible exterior wall constructed of fire retarded treated wood. The ignition resistance is determined in accordance with NFPA 285 (National fire protection association 2012). The test is also required to determine the vertical and lateral flame propagation for exterior walls that contain a combustible water resistive barrier in buildings of type I, II, III or IV construction that are taller than 12.2 m (40 feet).

Fire safety requirements for commonly used materials in façades such as metal composite materials (MCM), exterior insulation and finish systems (EIFS), high-pressure decorative exterior grade compact laminates (HPL), foam plastic insulation and fibre-reinforced polymer are specified in detail. The requirement for MCM, a flame spread index not more than 25 and a smoke-developed index not more than 250, is specified when tested in accordance with ASTM 84. For HPL those indexes are 75 and 450. Fire spread characteristics of foam plastic insulation are determined using a full-scale façade test in accordance with NFPA 285.

Alternatively, combustible material can be used provided that the complete façade assembly passes NFPA 285's test criteria. The test can be used to determine if a given wall assembly supports a self-accelerating and self-spreading fire up the wall, either outside the surface, through concealed spaces within the wall, or by spreading fire into interior floor areas on stories above. If the following are observed, the wall assembly fails the test (Valiulis 2015).

- A temperature > 1000 ºF at 3m (10 feet) or higher above the top of the window opening
- Flames visually observed on the exterior face of the specimen at 3 m (10 feet) or higher above the top of the window opening
- Flames visually observed on the exterior face of the specimen at 1.5 m (5 feet) or further from the centreline of the window opening
- Temperature rise > 750 ºF within any combustible wall components more than 6 mm (¼ inch) thick
- Temperature > 1000 ºF within any wall cavity air space
- Temperature rise > 500 ºF in the second story room, measured 25 mm (1 inch) from the interior surface of the wall assembly
- Flames visually observed within the second-story test room

4 COMPARISON OF STANDARD FIRE TESTS FOR FACADES

The following is an overview of the different façade fire test methods recognized by the NCC, ADB and IBC.

4.1 *Combustibility Test*

Standards Australia specifies the test method to determine the combustibility of building materials in accordance with AS 1530.1-1994 (Standards Australia 1994). This method does not apply to materials which are laminated, coated or faced. A separate fire test of each layer can be conducted to determine the fire performance of these products. AS 1530.1 requires cylindrical samples which are 45 mm in diameter and 50 mm in height (this is usually made by sandwiching thinner pieces of material together). A hole for a thermocouple is placed at the centre top of the specimen, which measures the temperature of the furnace and both the centre and surface of the specimen. After specimens are prepared, they are conditioned in a ventilated oven at 60 ±5 °C for 20 to 24 hours, and then cooled to ambient temperature in a desiccator prior to testing. Afterwards, specimens are placed inside a tube furnace at 750 °C, with a cone shaped stabilizer attached to the underside of the furnace. The NCC specifies a list of criteria for specimens to be not deemed combustible, namely: 1) there shall be no sustained flaming for more than 5 seconds, 2) the thermocouple does not show an increase in furnace temperature of more than 50 °C, and 3) the thermocouple does not show an increase in specimen surface temperature of more than 50 °C.

Combustibility of materials according to ADB is determined in accordance to BS EN ISO 1182 (British Standard Institute 2010). The sample preparation and test method is similar to AS 1530.1 but differs in the non-combustibility criteria. ISO 1182 specifies that the duration of continuous flaming shall not exceed 20 seconds. It also considers mass loss from the sample, which shall not exceed an average mass loss of 50 % of the original mass after the specimens are cooled down. Like AS 1530.1 the furnace temperature increase must not exceed 50 °C.

The IBC refers to ASTM E 136 (American society of testing and materials 2009) to classify materials as non-combustible. This test method is similar to ISO 1182 and AS 1530.1 and relies on the furnace temperature and arbitrary rise in thermocouples within specimens to assess temperature increase. There are two options but both use a furnace to expose materials to a 750 °C temperature. The first option involves a furnace with a ceramic tube which has an electric heating coil and two concentric vertical refractory tubes whereas the second option involves a furnace with refractory tube with a cone-shaped stabilizer. The detailed test method for the latter option is found under ASTM E2652 (American society of testing and materials 2016). In option A, at least four dry samples 38 mm x 38 mm x 51mm specimens are heated in a vertical tube furnace whereas in option B, 45 mm diameter x 50 mm high cylindrical samples are used. For both options, three of four specimens tested must pass the individual criteria to be deemed non-combustible. The criteria specify that if the weight loss of a specimen is 50 % or less, the following conditions must be met 1) the surface and interior thermocouples temperature rise is less than 30 °C 2) no specimen flaming occurs in the first 30 seconds. If the weight loss is more than 50 %, the criteria is: 1) no flaming at any time during the test, and 2) there is no surface and interior temperature rise.

4.2 *Fire ratings*

As indicated in the NCC, there are three performance criteria which are structural adequacy, integrity, and insulation. Non-load bearing elements, such as facades, are tested for integrity and insulation. Fire rating requirements for elements used in construction are determined from a standard fire-resistance test conducted in accordance with AS 1530.4 (Standards Australia 2005). The minimum size for the test specimens is 3 m x 3 m for vertical specimens and 4m x 3m for horizontal specimens. The thermocouples used to measure the furnace temperature are mineral insulated sheathed, 3 mm diameter, type K. The measuring system records temperatures at intervals not exceeding 1 minute. The furnace temperature is controlled to vary with time. A material that is exposed to a temperature prescribed in the standard ‘fire temperature vs time curve’ for a certain period of time is deemed to obtain a fire-resistance of *t.* The failure criteria in relation to integrity is said to have occurred if; 1) there is a continuous flaming on the surface of the unexposed face (non-fire side) for 10 s or longer, 2) ignition of a cotton pad within a period of 30 ±2 s, and 3) a 6 mm gap gauge can be passed through the specimen and can be moved a distance of 150 mm along the gap or a 25 mm gap gauge can be passed through the specimen. In relation to the insulation criteria, failure occurs if the temperature rise of relevant thermocouples, at any location on the unexposed face, is more than 180 K or when the average temperature rise of the unexposed face exceeds 140K.

ASTM E 119: *Standard Test Methods for Fire Tests of Building Construction and Materials* (American society of testing and materials 2016) is a fire test furnace method used to evaluate the fire performance of building construction sub-assemblies. For non-loadbearing walls and partitions, the area of the specimen exposed to the furnace fire is not less than 9 m^2. Prior to testing, specimens are conditioned at an ambient temperature of 50% relative humidity at 22.8 °C. Specimens are subjected to heat on one side with the furnace temperature controlled to the standard time-temperature curve prescribed in ASTM E 119 which is almost identical to AS 1530.4. The test continues until failure. Unexposed test specimen surface temperatures are measured with temperatures recorded at intervals not greater than 30 s. The test is successful when these conditions are met, namely: 1) there is no passage of flame hot enough to ignite cotton waste, 2) the specimen withstood a post-test hose stream test, and 3) the temperature rise through the specimen is not more than 139 °C above its initial temperature on its unexposed side.

4.3 *Full-scale façade test*

More recently, full-scale façade tests are being performed to replicate and understand the performance of assemblies under fire conditions. ISO 13785-2: Reaction-to-fire tests (International Organization for Standarization 2002) prescribes a test method to assess a post-flashover scenario, and fire performance of façade that is exposed to flames venting through a window opening or directly above its face. The test method consists of a combustion chamber, with an opening on one side, which is 2 m wide by 1.2 m high, and a façade specimen with a side wall. The total height of the test facility is 5.7 m. The test specimen is constructed such that a re-entrant corner exists between the main and wing façade walls. No particular type of fuel is specified in the standard and is left to the discretion of the testing laboratory but, propane gas with 95 % purity or an appropriate wood crib may be used. A total of eight heat flux meters are installed in the test facility and test specimen. Seven thermocouples are installed at the exterior surface of the test specimen. Prior to testing, the ambient temperature is between 10 °C and 30 °C. The front face of the façade is exposed to a heat flux of 55±5 kW/m^2, which is measured at a distance 0.6 m above the opening, and a maximum heat flux of 35±5 kW/m^2 at 1.6 m above the opening. The total duration of the test is between 23 and 27 minutes. The temperature of three thermocouples, positioned at the window opening, shall read a minimum temperature of 800 °C. Visual observations can be done during testing and after testing, heat flux meters installed at varying heights may be investigated. However, no performance criteria is indicated in the standard.

Full-scale façade tests are undertaken in the UK in accordance to BS 8414 (British Standard Institute 2015), which is a test method for non-loadbearing external cladding systems applied to the face of the building based on ISO 13785. The dimensions are similar to ISO 13785. The thermocouples are positioned at 0.9 m (if applicable), 2.5 m and 5 m (level 2) above the fire chamber. The assemblies are evaluated according to three characteristics: 1) external fire spread 2) internal fire spread, and 3) mechanical performance. The system is deemed to have failed under external fire spread when the temperature rise of any of the external thermocouples at level 2 exceeds 600 °C for a period of at least 30 seconds, within 15 minutes of the start time. For internal fire spread, the system is considered to have failed when the temperature rise of any of the internal thermocouples at level 2 exceeds 600 °C, for a period of at least 30 s within 15 minutes of the start time. Furthermore, there is no failure criteria set under mechanical performance however, details regarding spalling, delamination, and flaming debris are reported.

Standards Australia developed AS 5113: *Fire propagation testing and classification of external walls of buildings* (Standards Australia 2016), which is a test method that indicates the fire performance of wall claddings and assemblies, and the impact of fixing methods, thermal expansion of metals, etc. AS 5113 was adopted from ISO 13785-2 (International Organization for Standarization 2002) and BS 8414 (British Standard Institute 2015). AS 5113 uses the same sample size as ISO 13785 or BS 8414 along with their corresponding thermocouple locations.

Under external wall fire spread, the performance criteria that needs to be satisfied are the same as BS 476. However, there are two additional criteria which state that flame spread beyond the confines of the specimen in any direction shall not occur and falling debris is limited. The debris criteria limits the mass of debris falling off the specimen to 2 kg and there must be no continuous flaming on the ground for more than 20 seconds from any debris or molten material.

Where the system is attached to a wall that is not required to have an FRL of –/30/30 or 30/30/30 or more, the temperature on the unexposed face of the specimen 900 mm above the opening shall not exceed a 180 K rise and there should be no flaming or the occurrence of openings in the unexposed face of the specimen above the opening.

AS 5113 has included an additional criteria to evaluate the building-to-building fire spread. A separate test procedure is described in Appendix C which involves exposing the façade specimen to a 3 m x 3 m radiant heat source for a minimum of 30 minutes. If all the performance criteria given in clause 5.4.6 have been satisfied the façade is classified as BB”nn” where ‘nn’ kW/m^2 is the heat flux applied in the test. The required heat flux should be determined prior to the test from Table A2 which describes building-to-building fire spread requirement based on the distance to the adjacent building.

5 INFLUENCE OF FAÇADE PROPERTIES ON THE FIRE PERFORMANCE

5.1 *Cladding Materials*

Among the other factors which contribute to the fire performance of a façade, materials which the façade is made out of is the key component. Therefore, combustibility of the materials in a façade is the key characteristic that is tested to evaluate its compliance with fire safety regulations. The influence of some of the most commonly used materials in façades will be discussed in this section.

5.1.1 *Timber*

Timber is a widely used construction material especially for residential and low-rise buildings. With innovations such as Glued-laminated timber (glulam) and Cross-laminated timber (CLT)—timber has experienced an accelerating emergence as a primary material in multi-storey buildings. Despite being combustible, its low thermal conductivity and pyrolysis (chemical degradation when subjected to fire) allows it to be a stable structural element under fire (Frangi et al. 2008). When exposed to fire timber undergoes the following physical, chemical and structural changes.

- Heating: timber elements are heated and the moisture contained in its voids begins to evaporate.
- Pressurisation: The newly formed moisture generates a pressure build up, which causes a flow of vapour and liquid water.
- Pyrolysis: as heating of the timber continues it involves higher temperatures, generally up to 300 ºC, and pyrolysis takes place producing combustible gases, accompanied by a loss in mass (thermal degradation).
- Pyrolysis development: The pyrolysis front moves into virgin wood located at deeper positions and increases the temperature of the whole element.
- Charring: The char layer (partially burnt black coloured exterior) is not able to support any loads, causing an increase of the stress of the reduced section. However, it acts as thermal insulation for the remainder of the cross-section.

Innovative timber facades are being used in buildings with improvements making it suitable to adequately withstand fire (see Figure 5.1 and Figure 5.2).

Figure 5.1 A prefabricated timber facade used in building renovation (Malacarne et al. 2016)

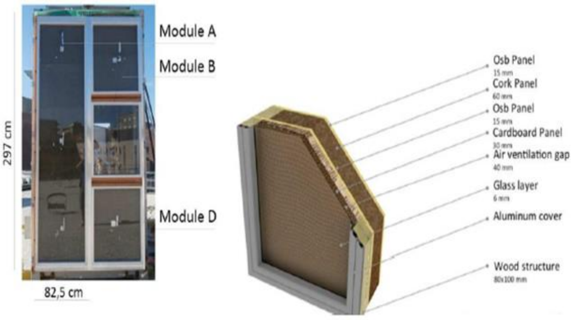


Figure 5.2 A solar timber facade system for building refurbishment (Callegari et al. 2015)

For uses in cladding, conventional timber sheets may not perform well under fire but recent studies show that CLT performs well, often having similar behaviour as non-combustible material (see Figure 5.3). Furthermore, the following passive fire protection methods can be used to limit the risk of fire spread (Giraldo et al. 2012).

- Application of flame retardant treatments to improve the reaction of the cladding material to fire
- Modified design the façade geometry;
    - To avoid the contact between the fire plume and the combustible cladding

- Provide deflector elements with the ability to change the trajectory of the flames and prevent its passage into other compartments

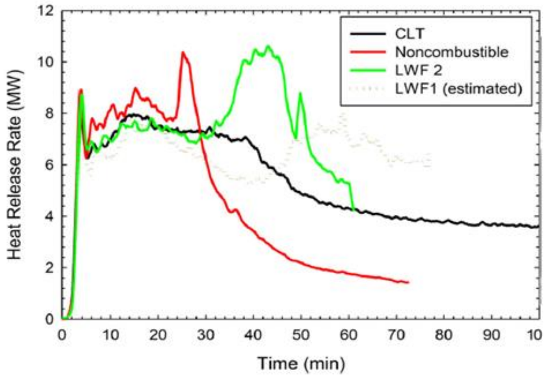


Figure 5.3 Heat release rate of fire development for different assemblies of non-combustible, light-weight wood frame and encapsulated CLT (Barber 2015)

5.1.2 *Glass*

The use of glass for external cladding is popular due to its transparency, aesthetic appearance and durability (Shao et al. 2016). With emerging concepts of green buildings aiming to reduce the energy consumption, glass facades are often a viable solution as they enable the effective use of sun light. Tempered glass, insulated glass, laminated glass and double-skin façades are some common types of glass facades used in buildings.

However, a glazed exterior is the weakest part of a building when subjected to a fire. Glass is prone to cracking and breakage under fire with minimum warning as a result of its brittle nature (Wang et al. 2017). This results in loss of façade integrity creating a channel for fresh air to enter forming a path to spread the fire outside the compartment of origin which accelerates fire development (Wang et al. 2017; Wang et al. 2014(b)). It highlights the fact that although glass is not a combustible material, the risk of fire spread due to glazing failure cannot be disregarded.

Experimental investigations have shown that cracking of glass depends on the location of fire and fixing position (Wang et al. 2014(a)). They conclude that the frame supported glass (Figure 5.4) façades are more prone to breakage when fire is located in the centre of a pane of point supported glass (Figure 5.4). Façades are also more prone to breakage when fire is positioned close to the fixing points (Wang et al. 2016).

Another study done on different types of glass facades show that insulated and laminated glass is more resistant to fire than single pane glass (Wang et al. 2017). Furthermore, laminated glass performs better due to the presence of a gel layer holding cracked glass together to effectively avoid the formation of a fire induced vent. Therefore, from a fire safety point of view, laminated glass is recommended for high-rise buildings over insulated and single pane glass due to its capability to prevent glass fallout and limit rapid fire spread to other floors. Chow evaluated double-skin façade systems consisting of two glass panes separated by a significant amount of air space, with thicknesses of the cavity ranging from 800 mm to 2 m (Chow et al. 2007). The inner glass skin is more likely to break in case of a room fire and smoke can spread to upper floors through the cavity than with a single pane (Ni et al. 2012).

Figure 5.4 Framed glass façade (Wang et al. 2014(b)) and point-supported glass façade (Wang et al. 2014(a))

5.1.3 *Composites*

Composite materials are used in facades to replace conventional materials such as steel, timber and concrete due to their high strength and stiffness properties combined with their low density and highly flexible shaping (Nguyen et al. 2014). The use of Aluminium Composite Panels (ACP), Fibre Reinforced Polymers (FRP), Glass Fibre Reinforced Polymers (GFRP) and Expanded Polystyrene (EPS) is discussed in this section.

5.1.3.1 Aluminium Composite Panels (ACP)

Aluminium composite panels (ACP) are flat panels made from aluminium composite materials (ACM), which consists of two or more layers bonded together. The primary components of ACPs are two outer aluminium sheets, coated with non-combustible PVDF paint or similar coatings, and then bonded together to a combustible polyethylene (PE) or PE combined with a non-combustible core or a combustible core. Aluminium is renowned as a flexible and durable material which can withstand extreme weather (water resistant) and resist the effects of harmful UV light (Stacey and Bayliss 2015). Hence, ACPs can last for a long period of time.

Available ACP products in the market come in different colours and sizes but are typically 3mm to 6 mm thick. ACPs are widely used for facades of buildings, cladding design for exterior or interior walls and columns, noise and thermal insulation, and signage. Some of the advantages of ACPs include easy installation, low maintenance, architecturally attractive, lightweight, with excellent façade skin properties.

A significant issue of ACP panels is their combustibility. Recent catastrophic events, as described in Section 2, have led to the understanding of how rapidly and easily fire propagates from floor to floor, with a fire originating from the façade system or an internal fire spreading to the façade system. This can be due to various factors, such as the use of combustible material or improper installation. Although this is a low frequency event, the impacts on life and properties can be significantly high.

5.1.3.2 Fibre Reinforced Polymer (FRP)

Architects increasingly use FRPs in modern buildings due to its ability to produce cost effective shapes, flexibility in aesthetics, durability and weathering resistance (Berardi and Dembsey 2015). However, the challenge lies with their fire resistance. FRPs possess a thermal conductivity (0.57 W/m·K) which is as low as wood and concrete. Experimental results show that FRPs have a low thermal transmissibility and a low fire pyrolysis behaviour (Berardi and Dembsey 2015). However, there is not enough conclusive evidence to evaluate the total behaviour under large scale fire conditions. Therefore, FRPs used in a façade must be subjected to large-scale façade fire testing.

5.1.3.3 Glass Fibre Reinforced Polymer (GFRP)

GFRPs are a special form of FRPs which has a very high strength to weight ratio, is durable and highly resistive to weathering and therefore a good choice for external cladding of buildings. A study on a façade containing GFRP composite facets and polyethylene foam core with the addition of fire retardant unsaturated polyester resins and gel coats shows that it might meet fire performance requirements related to heat release rate (Nguyen et al. 2014). However, smoke-related performance characteristics are problematic. Numerical analysis suggests that the use of resin mixed with the flame retardant aluminium hydroxide hydrate and gel coat might limit the smoke production rate. The applicability of GFRP façade panels in prefabricated modular building units were investigated in another study and it concluded that the fire performance of the unit with composite panels significantly exceeds conventional façade systems in terms of heat release rate (Ngo et al. 2016). Wall temperatures recorded were well below the standard time-temperature fire curve in the composite façade without glazing surfaces. However, although these are promising results, the safe use of GFRP is still not proven. In a similar study (Nguyen et al. 2016) the addition of 5 % Organoclay in GFRP prevented flashover from happening and horizontal flame spread and the fire growth index (FIGRA) and total heat release (THR) were well below the threshold level requirement for building materials according to standard EN 13501-1:2007. Further study of the use of this product is clearly warranted.

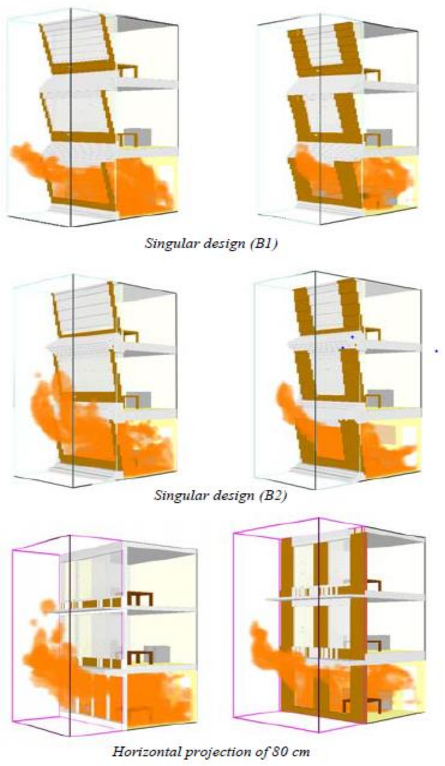
5.1.3.4 Expanded Polystyrene (EPS)

There are external thermal insulation composite facades incorporate EPS insulation with a thin rendering (finishing). Although the overall energy performance of the building is enhanced with such a system, the high combustibility of EPS poses a high fire risk on buildings with such facades (Hajduković et al. 2017). An experimental investigation carried out to find the influence of incident heat flux on façade and damage of the rendering showed a heat flux of 30 kW/m^2 was enough to crack the tested rendering. This was followed by internal burning of the EPS. Damaged rendering caused rapid fire spread along with release of smoke. EPS with a low melting point also increases the risk of a traveling fire source if proper encapsulation of EPS is not present. Therefore, extremely good workmanship and proper maintenance is necessary to ensure the safety of façade systems using EPS.

5.2 *Geometry*

Apart from cladding material, façade geometry also plays a key role in the risk fire propagation. Experimental and analytical studies have been carried out to find out the effect of façade geometry in fire.

Figure 5.5 shows results of a computational fluid dynamics (CFD) model to study the influence of different geometries of a wood cladding. Findings indicate that horizontal projections act as a flame deflector (Giraldo et al. 2012). Projections more than 60 cm were required to deflect the trajectory of the fire plume whereas projections greater than 80 cm are recommended to reduce the heat flow on the façade surface. Effect of the window size was also considered and as expected larger deflectors were required when the window size increased. These results are similar to those using non-combustible façade materials.


Singular design (B1)

Singular design (B2)

Horizontal projection of 80 cm

Figure 5.5 CFD model illustrating the difference of spread of fire for different facade geometry (Giraldo et al. 2012)

Another large scale experimental study was used to evaluate the influence of a U-shaped façade geometry (as shown in Figure 5.6) on fire behaviour. It found that such a geometry would increase the fire hazard as the flame spread rate and flame height is increased as a result of the U-shape geometrical factor (Yan et al. 2017). The well-known 2010 façade fire in Shanghai, China showed how a U-shaped façade geometry could fuel a rapid fire spread.

Figure 5.6. U-shaped facade wall geometry and a fire occurred in a building with U-shaped facade, Shanghai, China, 2010 (Yan et al. 2017)

An experimental study carried out to find the effect of a sloping wall (similar to a hill side slope adjacent to a building) concluded that the façade flame height increases with the increase in sloping wall angle, especially over 60 ºC (Tang et al. 2015). The heat flux to the façade has increases sharply at larger sloping face wall angles. Kings Cross station fire in London, 1987 is another incident where the geometry significantly influenced the rapid fire spread. Investigations revealed that the trench effect which occurs when a fire burns besides a steeply inclined surface has aggravated the flame spread (Sharples et al. 2010).

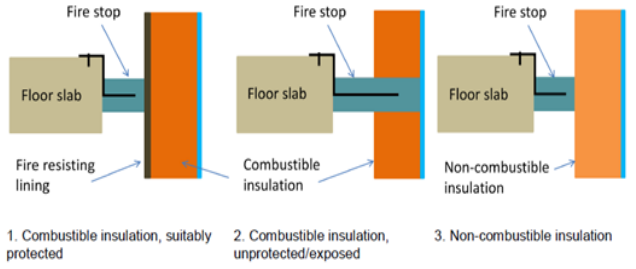
Research findings on the influence of façade geometry on fire propagation highlights that a careful attention should be made to the potential of the spandrel effect in façades especially when combustible materials are involved.

5.3 *Cavities*

There are two primary types of façade cavities; cavities within the cladding element and cavities between cladding (also known as rain screen) and the external wall. Depending on the type of cladding used and façade configuration either one type or both types of cavities can be present in a building. The risk of such cavities is that they provide a passageway for both heat and smoke to spread rapidly.

A double-skinned façade (DSF) is a glass architectural feature where a cavity is present within the cladding element (between the inner skin and the outer skin). The depth of the cavity may range from 800 mm to 2 m to improve environmental performance by inducing air flow to take away the heat trapped in the gap (Chow et al. 2007). Several studies were conducted on the smoke and heat transfer through this gap (Chow 2014; Chow et al. 2007; Ji et al. 2016) and the critical scenario is predicted to happen when the inner pane cracks while the outer pane is still intact. This will cause smoke to spread inside a building and worsen the indoor conditions, possibly affecting occupant egress. It was found that a cavity depth of 1 m is the most risky arrangement while an increased depth will drive smoke towards the outer pane and a reduced depth will cause the outer pane to crack without damaging the inner pane (Chow et al. 2007). Furthermore, an outward tilted outer pane would reduce the risk as an inward tilted or vertical outer pane speeds up smoke movement adhering to the inner pane of the cavity (Ji et al. 2016).

Cavities between the cladding and the external wall are a common feature in multi-storey buildings. In the case of a façade fire, fire and smoke spread through such cavities may be more rapid than on the outside of the face of the cladding (Centre for Window and Cladding Technology 2017). To prevent such damage, fire stops and cavity barriers can be provided within the façade assembly (Buchanan 2001). There are various methods of detailing fire stop and Figure 5.7 shows typical arrangements of fire stops for a curtain wall system.



1. Combustible insulation, suitably protected
2. Combustible insulation, unprotected/exposed
3. Non-combustible insulation

Figure 5.7 Fire-stop detailing for a curtain wall(Centre for Window and Cladding Technology 2017)

Cavity barriers are also similar to fire stops, installed in between the cladding panel and the external wall both in the horizontal and the vertical directions (Figure 5.8) to block the pathway of flames and smoke. Intumescent materials are often used in horizontal cavity barriers to allow a cavity to be maintained under normal circumstances but to seal the cavity in the event of a fire (Centre for Window and Cladding Technology 2017). Large scale tests done at BRE have found that cavity barriers with a continuous strip of intumescent material are more effective than those with perforated plates (Centre for Window and Cladding Technology 2017).

Figure 5.8. Vertical and horizontal cavity barriers attached before installing the cladding panels (BRE Global Ltd 2017)

5.4 *Other influencing parameters*

5.4.1 *Wind*

The effect of wind on façade fires is mainly two-fold; ventilation at the fire source which impacts the heat release rate and the external wind that impacts the fire and smoke spread along the cladding. Studies have found that an air supply directly blowing on a fire source has a significant effect on the heat release rate of the fire (Gao et al. 2017).

External wind is another contributor to the spread of flame and smoke especially in multi-storey buildings. There are only a few studies investigating this phenomenon. One study suggests that the façade fire flame height decreases with increasing external wind speed (Hu et al. 2017). However, the wind was directed on the flame and applied normal to the external face of the building in this experiment. Another limitation of this study is that the façade had only one opening, which is not the case in most buildings. Another study done on a compartment with dual symmetric openings, under cross wind conditions, concluded that wind enhances the air entrainment of the spill plume in both the near and far fields, thereby accelerating the transition from continuous flame to intermittent flame to buoyant plume (Gao et al. 2016) (See Figure 5.9).

Furthermore, the importance of identifying the main directions of cross-wind and taking into account the potential of fire swirling when designing the maximum height of tall buildings was highlighted.

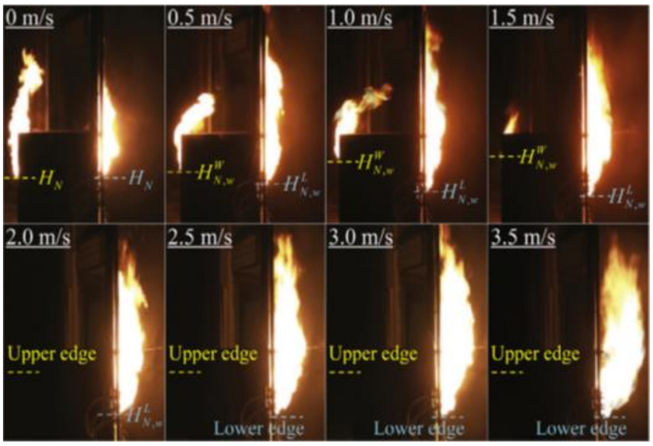


Figure 5.9 Experimental photos of spill plumes under different wind speeds(Gao et al. 2016)

5.4.2 *Space between buildings*

Building to building fire spread and the spread of fire along a building's exterior can be influenced by the space between adjacent buildings. Radiation from a fire poses a risk to adjacent buildings as when the radiation heat flux exceeds the critical ignition heat flux of combustible materials in the exterior of the adjacent building, fire will spread from one building to another (Cheng and Hadjisophocleous 2012). This could be critical in an urban metropolitan area where multi-storey buildings are situated close to one another.

To enhance fire safety, building codes such as the NCC require buildings to satisfy separate performance criteria (for buildings on the same allotment and buildings on separate allotments) specifying limiting heat flux values depending on the separation distance. However, there are certain arguments that these two criteria are inconsistent and highlight the need for revision using a sound scientific basis (Poh 2017).

Another knowledge gap exists concerning the behaviour of flame swirling when a fire occurs in the passage of the vortices behind an adjacent tall building (Chen et al. 2009).

6 FLAME AND SMOKE SPREAD PREDICTION TECHNIQUES -NUMERICAL STUDIES

The assessment of the fire performance of a façade depends on the determination of the flame and smoke spread and the potential damage. Experimentally these criteria can be evaluated in accordance with standard façade test methods described in section 4. Those experiments would measure the temperature and flame height to provide a holistic idea into how a specific façade assembly will perform under fire. However, when such facilities are not available there should be different methods to predict the flame and smoke spread.

Flame and smoke can spread either through the cavities or through the exterior face of the façade. To predict the spread, analytical models that involve mathematical equations related to heat transfer are being used. With the development of computational fluid dynamics (CFD) techniques, several studies have been performed to evaluate façade performance in fire (See Figure 6.1).

The limitation of the mathematical model is that it can only be applied to a specific scenario. Models have been developed for cases such as the spread of smoke and heat along a narrow air cavity in a double-skin façade (Chow 2014; Ding and Hasemi 2006; Ji et al. 2016), flame height and temperature of externally ventilated fire (Asimakopoulou et al. 2016; Asimakopoulou et al. 2017; Asimakopoulou et al. 2017) and under-ventilated compartment fires (Hu et al. 2015; Tang et al. 2012) and the temperature profile of a window ejected fire with adjacent side walls (Lu et al. 2014; Lu et al. 2017). Detailed derivation of the models can be found in the cited literature. The advantage of using CFD modelling is that more information can be extracted from a model than is typically available in a fire test. A major limitation is that the ability to model flame spread on a combustible material is extremely limited (Kwon et al. 2007).

In both mathematical models and CFD models it is important to define the correct thermal boundary conditions. Incorporating the contribution of façade material flammability for fire spread tends to provide more accurate results (Nguyen et al. 2016). On a concluding remark, both mathematical and CFD models have advantages and limitations depending on their specific application. Incorporating both methods together would be effective. A mathematical model can be used in the initial stage before CFD model to improve the accuracy.

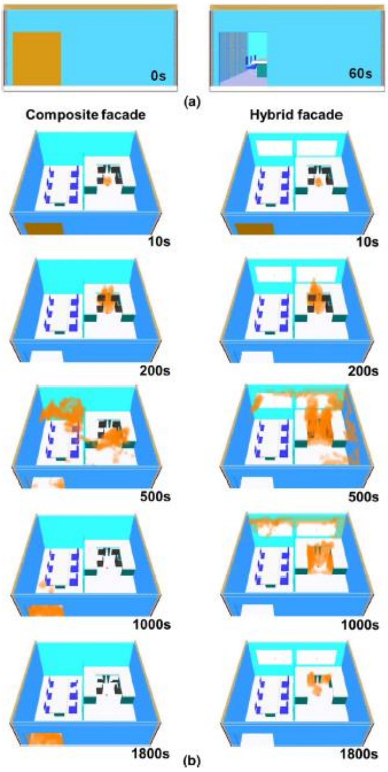


Figure 6.1 Fire dynamics simulator model of a composite facade and a hybrid façade (Ngo et al. 2016)

7 CONCLUSION

Different types of façade panels are used around the globe, but recent catastrophic events have forewarned the industry of the need to develop an understanding of the fire behaviour of modern façade. The influence of different façade properties, especially combustibility, was presented as a key characteristic that needs to be checked for compliancy. Among the other factors affecting the fire performance of façade elements are the geometry, cavities, and external factors such as wind and spaces between buildings. Geometry greatly impacts the rapid spread of fire. The cavities between the external wall and the façade element, and within the façade element itself also impact the fire hazard. A comparison of the different test methods recognized by the NCC, ADB and the IBC are presented to help gain an understanding of the different test principles, in which façade elements are designed for fire safety. Although these standards and advanced techniques such as CFD modelling exist, there are still difficulties in representing the actual fire scenarios and in predicting actual fire behaviour that needs further research.

8 REFERENCES

American society of testing and materials (2009). "ASTM E136 Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C."

American society of testing and materials (2016). "ASTM E119 Standard Test Methods for Fire Tests of Building Construction and Materials."

American society of testing and materials (2016). "ASTM E2652 Standard Test Method for Behavior of Materials in a Tube Furnace with a Cone-shaped Airflow Stabilizer, at 750°C."

Asimakopoulou, E. K., Kolaitis, D. I., and Founti, M. A. (2016). "Geometrical characteristics of externally venting flames: Assessment of fire engineering design correlations using medium-scale compartment-façade fire tests." *Journal of Loss Prevention in the Process Industries*, 44, 780-790.

Asimakopoulou, E. K., Kolaitis, D. I., and Founti, M. A. (2017). "Assessment of fire engineering design correlations used to describe the geometry and thermal characteristics of Externally Venting Flames." *Fire Technology*, 53(2), 709-739.

Asimakopoulou, E. K., Kolaitis, D. I., and Founti, M. A. (2017). "Thermal characteristics of externally venting flames and their effect on the exposed façade surface." *Fire Safety Journal*.

Austin, H., and Williams, R. (2015). "Dubai skyscraper fire: Blaze rips through Torch residential tower block in city's marina district." <http://www.independent.co.uk/news/world/middle-east/dubai-skyscraper-fire-blaze-rips-through-torch-residential-building-in-marina-district-10061013.html>. (2017.07.18).

Australian Building Codes Board (2016 (a)). "Advisory Note: Fire Performance of External Walls and Cladding."

Barber, D. (2015). "Tall Timber Buildings: What's Next in Fire Safety?" *Fire Technology*, 51(6), 1279-1284.

Barboza, D. (2010). "Workers Detained as Toll Hits 53 in Shanghai Fire." <http://www.nytimes.com/2010/11/16/world/asia/16shanghai.html?mcubz=2>. (2017.07.18).

Berardi, U., and Dembsey, N. (2015). "Thermal and Fire Characteristics of FRP Composites for Architectural Applications." *Polymers*, 7(11), 2276-2289.

BRE Global Ltd (2017). "BRE Global client report on full-scale fire testing of facade ", Building Research Establishment, UK.

British Standard Institute (2010). "BS EN ISO 1182:2010 Reaction to fire tests for products. Non-combustibility test."

British Standard Institute (2015). "BS 8414-1:2015 Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems."

Buchanan, A. H. (2001). *Structural design for fire safety*, John Wiley & Sons.

Building Control Alliance (2015). "Technical Guidance Note 18: Use of Combustible Cladding Materials on Buildings Exceeding 18m in Height."

Callegari, G., Spinelli, A., Bianco, L., Serra, V., and Fantucci, S. (2015). "NATURWALL©-A solar timber façade system for building refurbishment: optimization process through in field measurements." *Energy Procedia*, 78, 291-296.

Centre for Window and Cladding Technology (2017). "Technical Note 98 : Fire performance of facades - Guide to the requirements of UK Building Regulations."

Chen, Z., Satoh, K., Wen, J., Huo, R., and Hu, L. (2009). "Burning behavior of two adjacent pool fires behind a building in a cross-wind." *Fire Safety Journal*, 44(7), 989-996.

Cheng, H., and Hadjisophocleous, G. V. (2012). "Experimental study and modeling of radiation from compartment fires to adjacent buildings." *Fire Safety Journal*, 53, 43-62.

Chow, L. C. (2014). "Spread of smoke and heat along narrow air cavity in double-skin façade fires." *Thermal Science*, 18(suppl. 2), 405-416.

Chow, W., Hung, W., Gao, Y., Zou, G., and Dong, H. (2007). "Experimental study on smoke movement leading to glass damages in double-skinned façade." *Construction and Building Materials*, 21(3), 556-566.

Cockburn, H. (2017). "Russia hotel fire: Two dead after blaze engulfs 10-storey building in Rostov on Don." <http://www.independent.co.uk/news/world/europe/russia-hotel-fire-two-dead-10-storey-building-video-rostov-on-don-oblast-a7960996.html>.

Department of Communities and Local Government (2010). "Fire Safety: Approved Document B - Volume 2."UK.

Ding, W., and Hasemi, Y. (2006). "Smoke Control Through a Double-Skin Façade Used for Natural Ventilation." *ASHRAE transactions*, 112(1).

Duval, B. (2008). "Monte Carlo Hotel Casino Fire." <http://www.nfpa.org/news-and-research/publications/nfpa-journal/2008/may-june-2008/features/monte-carlo-hotel-fire>. (2017.07.18).

European Committee for Standarization (2009). "EN 13501-1:2009 Fire Classification Of Construction Products And Building Elements - Part 1: Classification Using Data From Reaction To Fire Tests."

European Committee for Standarization (2014). "EN 1364-4:2014 Fire resistance tests for non-loadbearing elements. Curtain walling. Part configuration."

Everett, R. (2018). "'Controlled chaos' as rescuers scrambled to save lives in high-rise fire." <http://www.nj.com/atlantic/index.ssf/2018/01/dispatch_audio_firefighters_evacuate_disabled_seni.html>.

Farrer, M., and Barney, L. (2017). "Honolulu fire: three dead after blaze breaks out in high-rise building." <https://www.theguardian.com/us-news/2017/jul/15/honolulu-fire-more-than-60-firefighters-tackle-blaze-at-high-rise-building>. (2017.09.20).

FPA (2012). "High-rise blaze in 18-storey block in Roubaix, France."

<http://www.blog.plumis.co.uk/2012/05/high-rise-blaze-in-18-storey-block-in.html>. (2017.07.18).

Frangi, A., Fontana, M., and Knobloch, M. (2008). "Fire Design Concepts for Tall Timber Buildings." *Structural Engineering International*, 18(2), 148-155.

Gao, R., Fang, Z., Li, A., Shi, C., and Che, L. (2017). "Estimation of building ventilation on the heat release rate of fire in a room." *Applied Thermal Engineering*, 121, 1111-1116.

Gao, W., Liu, N., Delichatsios, M., Yuan, X., Bai, Y., Chen, H., and Zhang, L. (2016). "Fire spill plume from a compartment with dual symmetric openings under cross wind." *Combustion and Flame*, 167, 409-421.

Giraldo, M. P., Avellaneda Diaz-Grande, J., Lacasta Palacio, A. M., and Rodríguez, V. "Computer-simulation research on building-facade geometry for fire spread control in buildings with wood claddings." *Proc., Proccedings of the World Conference on Timber Engineering 2012*, 1-8.

Hajduković, M., Knez, N., Knez, F., and Kolšek, J. (2017). "Fire performance of external thermal insulation composite system (ETICS) facades with expanded polystyrene (EPS) insulation and thin rendering." *Fire Technology*, 53(1), 173-209.

Hu, L., Hu, K., Ren, F., and Sun, X. (2017). "Facade flame height ejected from an opening of fire compartment under external wind." *Fire Safety Journal*, 92, 151-158.

Hu, L., Qiu, Z., Lu, K., and Tang, F. (2015). "Window ejected flame width and depth evolution along facade from under-ventilated enclosure fires." *Fire Safety Journal*, 76, 44-53.

International Code Council (2012). "International Building Code."US.

International Organization for Standarization (2002). "ISO 13785-2:2002 Reaction to fire tests for facades - Part 2: Large-scale test."

Ji, J., Li, Y. F., Shi, W. X., and Sun, J. H. (2016). "Numerical studies on smoke spread in the cavity of a double-skin façade." *Journal of Civil Engineering and Management*, 22(4), 470-479.

Kirkpatrick, D. D., Hakim, D., and Glanz, J. (2017). "Why Grenfell Tower Burned: Regulators Put Cost Before Safety." <https://www.nytimes.com/2017/06/24/world/europe/grenfell-tower-london-fire.html?mcubz=2>. (2017.07.18).

Kwon, J.-W., Dembsey, N. A., and Lautenberger, C. W. (2007). "Evaluation of FDS V. 4: upward flame spread." *Fire technology*, 43(4), 255-284.

Lu, K., Hu, L., Tang, F., He, L., Zhang, X., and Qiu, Z. (2014). "Heat flux profile upon building facade with side walls due to window ejected fire plume: An experimental investigation and global correlation." *Fire Safety Journal*, 70, 14-22.

Lu, K., Wang, J., and Hu, L. (2017). "Vertical temperature profile of fire-induced facade thermal plume ejected from a fire compartment window with two adjacent side walls." *Applied Thermal Engineering*, 113, 70-78.

Malacarne, G., Monizza, G. P., Ratajczak, J., Krause, D., Benedetti, C., and Matt, D. T. (2016). "Prefabricated Timber Façade for the Energy Refurbishment of the Italian Building Stock: The Ri. Fa. Re. Project." *Energy Procedia*, 96, 788-799.

Miers, P. (2016). "Fire Risks From External Cladding Panels – A Perspective From The UK ".

National fire protection association (2012). "NFPA 285: Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components."

Ngo, T. D., Nguyen, Q. T., and Tran, P. "Heat release and flame propagation in prefabricated modular unit with GFRP composite facades." *Proc., Building Simulation*, Springer, 607-616.

Nguyen, Q., Ngo, T., Tran, P., Mendis, P., Zobec, M., and Aye, L. (2016). "Fire performance of prefabricated modular units using organoclay/glass fibre reinforced polymer composite." *Construction and Building Materials*, 129, 204-215.

Nguyen, Q. T., Tran, P., Ngo, T. D., Tran, P. A., and Mendis, P. (2014). "Experimental and computational investigations on fire resistance of GFRP composite for building façade." *Composites Part B: Engineering*, 62, 218-229.

Ni, Z., Lu, S., and Peng, L. (2012). "Experimental study on fire performance of double-skin glass facades." *Journal of fire sciences*, 30(5), 457-472.

Poh, W. (2017). "Dissecting BCA verification methods."Fire Australia Conference

Reuters (2015). "17 dead in Azerbaijan as high-rise combusts in seconds." <https://www.rt.com/news/260125-azerbaijan-building-fire-fatal/>. (2017.07.18).

Schreck, A., and Gambrell, J. (2016). "How a common building material turned a Dubai hotel fire into an inferno." <https://www.thestar.com/business/2016/01/19/how-a-common-building-material-turned-a-dubai-hotel-fire-into-an-inferno.html>. (2017.07.18).

Shao, G., Wang, Q., Zhao, H., Wang, Y., Sun, J., and He, L. (2016). "Thermal breakage of tempered glass façade with down-flowing water film under different heating rates." *Fire Technology*, 52(2), 563-580.

Sharples, J. J., Gill, A. M., and Dold, J. W. (2010). "The trench effect and eruptive wildfires: lessons from the King’s Cross underground disaster." *Proceedings AFAC 2010*.

Stacey, M., and Bayliss, C. (2015). "Aluminium and Durability: Reviewed by Inspection and Testing." *Materials Today: Proceedings*, 2(10, Part A), 5088-5095.

Standards Australia (1994). "AS 1530.1-1994(R2016) Methods for fire tests on building materials, components and structures Combustibility test for materials."

Standards Australia (1999). "AS 1530.3-1999 Methods for fire tests on building materials, components and structures. Part 3: Simultaneous determination of ignitability, flame propagation, heat release and smoke release."

Standards Australia (2005). "AS 1530.4-2005 Methods for fire tests on building materials, components and structures Fire-resistance test of elements of construction."

Standards Australia (2016). "AS 5113:2016 Fire propagation testing and classification of external walls of buildings."

Tang, F., Hu, L., Delichatsios, M., Lu, K., and Zhu, W. (2012). "Experimental study on flame height and temperature profile of buoyant window spill plume from an under-ventilated compartment fire." *International journal of Heat and Mass transfer*, 55(1), 93-101.

Tang, F., Hu, L., Qiu, Z., Zhang, X., and Lu, K. (2015). "Window ejected flame height and heat flux along facade with air entrainment constraint by a sloping facing wall." *Fire Safety Journal*, 71, 248-256.

The Australian Building Codes Board (2016 (b)). "National construction code - 2016 Building code of Australia."

The Australian Building Codes Board (2018). "National construction code 2016 - Volume one Amendment 1."

Toscano, N., and Spooner, R. (2015). "Docklands apartment tower fire fuelled by material in building's walls, says MFB." <http://www.theage.com.au/victoria/docklands-apartment-tower-fire-fuelled-by-material-in-buildings-walls-says-mfb-20150427-1mukhx.html>. (2017.07.18).

Valiulis, J. (2015). "Building Exterior Wall Assembly Flammability: Have we forgotten what we have learned over the past 40 years?", Fire Safety North America.

Victorian Building Authority (2016). "VBA External Wall Cladding Audit Report."

Wang, Y., Wang, Q., Su, Y., Sun, J., He, L., and Liew, K. (2017). "Experimental study on fire response of double glazed panels in curtain walls." *Fire Safety Journal*, 92, 53-63.

Wang, Y., Wang, Q., Sun, J., He, L., and Liew, K. (2014(a)). "Effects of fixing point positions on thermal response of four point-supported glass façades." *Construction and Building Materials*, 73, 235-246.

Wang, Y., Wang, Q., Sun, J., He, L., and Liew, K. (2016). "Influence of fire location on the thermal performance of glass façades." *Applied Thermal Engineering*, 106, 438-442.

Wang, Y., Wang, Q., Wen, J. X., Sun, J., and Liew, K. (2017). "Investigation of thermal breakage and heat transfer in single, insulated and laminated glazing under fire conditions." *Applied Thermal Engineering*, 125, 662-672.

Wang, Y., Wu, Y., Wang, Q., Liew, K., Chen, H., Sun, J., and He, L. (2014(b)). "Numerical study on fire response of glass facades in different installation forms." *Construction and Building Materials*, 61, 172-180.

Yan, W., Jiang, L., An, W., Zhou, Y., and Sun, J. (2017). "Large scale experimental study on the fire hazard of buildings' U-shape façade wall geometry." *Journal of Civil Engineering and Management*, 23(4), 455-463.