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Evaluating the fire risk associated with cladding panels: An overview of fire incidents, policies, and future perspective in fire standards

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Summary

Multifunctional building façades have become an increasingly critical component in modern buildings, especially after the tremendous scrutiny triggered by the utilization of combustible aluminum cladding panels (ACP) in the construction sector. Following the massive effort by both industry and government agencies to reduce the fire risks of combustible façades in recent years, façades with insufficient fire ratings have been continuously causing severe building fires leading to countless human casualties and properties damages. This review aims to provide an in-depth overview of the previous developments and current progress for establishing relevant fire standards with regards to ACPs, from an Australian standpoint. The fire spread mechanisms associate with ACPs, and their potential hazards were discussed. Furthermore, the current building regulations for ACPs have been reviewed, including detailed experimental procedures and rating criterion for all existing international standards. To address the research knowledge gap in terms of the understanding of the cladding fire mechanisms, and combustibility of existing ACP polymer composites, recent advancement in experimental and numerical studies has been summarized and discussed to identify the critical issues and concerns for current ACP products. Future perspectives involving cutting-edge approaches such as computational fluid dynamics (CFD) modeling coupled with artificial neural network (ANN) optimization are advocated in this article. Additionally, fundamental material characterization techniques using molecular dynamics (MD) approaches can be implemented to deliver a better description of the degradation kinetics and smoke/toxicity generations.

KEYWORDS
aluminum composite panels, building composite, building façade, building fire, cladding fire, fire risk

1 | INTRODUCTION

The Grenfell Tower fire in 2017, which was a tragic fire incident that occurred over in a 24-storey building, has unfortunately taken 72 lives

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and caused billions of property damage. Through fire investigations, it was identified the fire was initiated by an electronic malfunction, yet the fire became uncontainable owing to its rapid propagation on the external wall system, particularly the aluminum cladding panel (ACP). The external fire engulfed the entire building bringing flame and smoke to almost all the residential floors. This incident has triggered an enormous international backlash on the use of combustible ACPs in the construction sector. Ever since, there has been a massive effort by both industry and government agencies to reduce the fire risks of combustible façades in buildings; these actions include (a) large-scale auditing of high-rise building facades[1,2] and remediation works,[3] (b) overhaul of the building regulation and standards,[4,5] and (c) significant research projects on topics such as fire risk analysis,[6-8] development of new materials,[9,10] and fire preventive measures.[11] Despite these considerable efforts, there is still an increasing trend for the number of fires in tall buildings with fire spread via the external walls worldwide. Bonner et al[12] reported the total number of large façade fires globally had increased seven times in the last 30 years, and the data only accounted for large fires reported by the media. Furthermore, combined with the rapid urbanization and population growth trends facing many major global cities, the increasing number of high-rise and high-density residential environments has amplified the fire risks of combustible cladding materials, and it remains a challenge to this day.

ACPs are generally composed of a thin outer metal skin of steel or aluminum and cores of insulating material which often include highly combustible expanded polystyrene or polyurethane and sometimes low-density polyethylene, as well as mineral fiber. They are often found in exterior cladding systems or otherwise known as exterior insulation finishing systems (EIFS) or external thermal insulation composite systems (ETICS). The existing exterior wall assemblies can vary, including many types, such as exterior insulation finish system (EIFS),[13-18] metal composite material cladding,[19-21] high-pressure laminates,[22-24] structural insulation panel system (SIPS),[25-28] rain screen cladding (RSC),[29-33] weather-resistive barriers,[34] external timber panelling,[35,36] and so on. These assemblies can typically be installed as the external cladding or covering a solid structural external wall and also can be a curtain wall system. ACPs are commonly made up of two thin aluminum sheets bonded to a polymer core. The most used variety is the PE, which is the highest risk ACP products with a 100% polymer core (usually polyethylene). Also, there are many varieties of ACP, such as ACP FR, ACP A2, and aluminum honeycomb, which are shown in Figure 1.

ACPs have been receiving much focus in the cladding fire challenge, and the remediation and mitigation efforts have been heavily concentrated on these materials. Fundamentally, ACPs are the symptom of a more significant problem, and the fire risk of other flammable components within a cladding must equally be assessed. These include high-pressure laminates, timber claddings, weatherproof membranes, and insulation.[37] The problem is particularly difficult as these materials are included as part of a system that has interactions between components and introduces the issue of elements such as mechanical fixings. Many of the remediation strategies around the world have yet to address whether or not non-ACP materials pose a risk for the specific buildings they are included within. Figure 2 illustrates the sandwiched structure and the flammable core of the ACPs. Furthermore, the potential for a cladding system to contribute to significant fire propagation increases with the flammability of the materials used, the complexity of the cladding structure, and the way in which the cladding is attached to the building. Other than the high-flammable core found in ACP, many other factors influence the fire safety of exterior cladding systems. These include the width of the cavity between the insulation and the external panels, the types of insulation material, the installation of fire barriers in between levels, the structural weaknesses of joints, and the connection between individual panels that deteriorate when exposed to high temperature. Unfortunately, relevant legislation and building codes have yet to catch up with the requirements for assessing the fire risks involved in these buildings, and many key aspects of exterior facade flammability remain not well understood. Therefore, it is important to develop a systematic approach to evaluate the risks for the existing and ongoing development of combustible cladding materials (ie, ACP) that could be applicable to a wide range of building configurations.

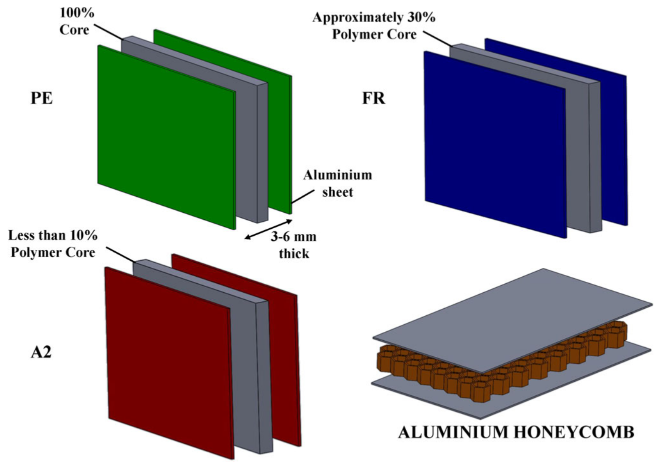


FIGURE 1 Schematic diagrams for different ACP products

This review aims to present a comprehensive review of relevant past fire events involving noncompliant building materials. These incidents have been analyzed according to the fire causes, propagation mechanisms, damage, and response by the relevant fire authorities to gain a deeper understanding of the impact of noncompliant building products on fire safety and the potential fire risks being exposed to building occupants. Also, this review will provide an overview of the impact of building ACP products on fire safety and the potential fire risks. The experimental works, including taskforce work in Australia, fire test methods, and an elementary database of cladding materials, as well as the simulation studies on cladding fires, are also reviewed. Furthermore, a future multiscale modeling framework is also discussed for fire safety engineering design and analysis of building façade materials in practical building fires and fire investigation studies. Specifically, the following are the major topics covered in the article:

1. An overview of past fire scenarios for cladding and external wall fires, to provide an in-depth understanding of the external fire phenomena and identify the underlying fire spread mechanisms for ACPs.

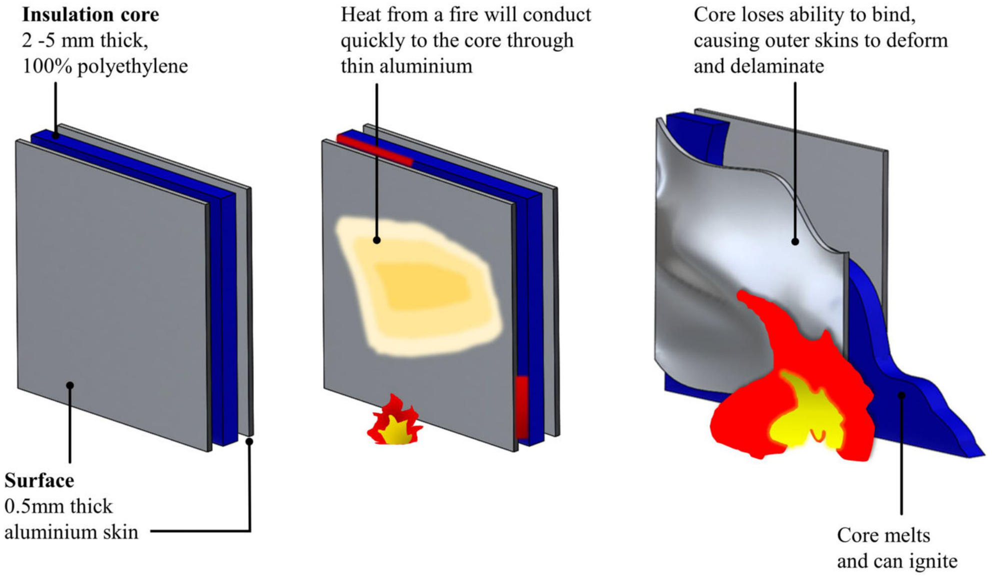


FIGURE 2 Configuration of ACP products[38,39]

2. According to the fire spread mechanisms, further breakdown to potential fire risks and hazards specifically for building fires involving ACPs.
3. Reveal the international building codes, fire testing standards for compliance check of ACP products. Additionally, summarize the contributions, achievements, and upcoming work for the Australian state government task forces.
4. Based on major fire experiments and research on combustible ACPs, summarize the fire performance and rating for various types of ACPs with different configuration and polymer cores.
5. Provide a future perspective in the area of research for reducing the fire risks for ACPs. Furthermore, proposing alternative approaches including machine learning algorithms–assisted computational simulations for fire predictions and molecular dynamics (MD) simulation to gain a fundamental understanding of the smoke/toxicity productions of the ACPs.

A detailed outline of this review is as follows: Section 2 presents an extensive review of past fire cases involving combustible ACP materials. Through analysis of the past fire cases, key potential fire risks associated with cladding façade systems will be identified and discussed in section 3. Section 4 presents a review of the current cladding standards and government taskforces. Section 5 presents a comprehensive review of existing studies and methodologies related to ACP and façade fires from both experimental and numerical simulation approaches. Lastly, based on all the review work in previous sections, future prospects and key research trends are discussed in detail.

2 | REVIEW OF PAST FIRE CASES

In the past decades, composite panels were developed as a cost-effective and lightweight building material that can be rapidly installed as an external cladding or facades for the buildings. Throughout continuous development over the past decades, composite panels are extensively applied across a vast variety of buildings for cosmetic and heat management functions nowadays. Such extensive application of ACP can be ascribed to its flexibility in shaping, excellent characteristics in terms of insulation, durability, and weighting. However, the increasingly widespread use of composite panels also sparks concern in relation to their fire risks. In this section, three major fire risks will be introduced through reviewing significant fire cases involving combustible external cladding materials in the past decades; a chronographic summary of the cases will also be presented in the end. The fire incidents reviewed in this research are summarized in the following table.

2.1 | Rapid surface propagation

From the reviewed cases in Table 1, cladding materials generally consist of aluminum panels, highly combustible expanded polystyrene or polyurethane, and sometimes low-density polyethylene. These materials contribute to the rapid-fire propagation along the external surfaces, which can be evidently observed in all of the reviewed cases. The propagation would usually occur as an uncontrollable blaze within 10 to 20 minutes from the initial ignition.[49,50,52,54,60]

The thermal characteristics of the material utilized in the cladding system contributed to the rate of fire spread. From the reviewed cases, the melting of insulation and burning droplets (ie, extruded polystyrene) would flow downward along the surface and enter the building causing the fire to propagate downwards rapidly.[48,50,58] In specific cases, uncontrollable propagation would even compromise the building structure and lead to internal structure collapse.[41] The China Shanghai Apartment fire in 2010, which was one of the most tremendous fire incidents involving cladding materials in history, has caused 58 fatalities and injuring 71 people in the 28-storey residential building (Figure 3).[53] The high flammability of the polyurethane foam

TABLE 1 A summary of the reviewed fire incidents

Building	Location	Year	Damage	References
Knowsley Heights Fire	Liverpool, UK	1991	No injuries	40
Sun Valley Fire	Hereford UK	1993	2 Fatalities	41
Garnock Court Fire	Scotland	1999	No injuries	42
Tip Top Bakery Fire	NSW, Australia	2002	Total loss in excess of $100 Million	43
The Water Club	USA	2007	Massive falling structural debris	44
MGM Monte Carlo Hotel	USA	2008	13 Minor injuries	45-47
Lakanal House Fire	London	2009	6 Fatalities	48
Miskolc Fire	Hungary	2009	3 Fatalities, including 2 children	49
Television Cultural Centre Fire	China	2009	1 Fatality, 7 injuries	50
Wooshin Golden Suites Fire	South Korea	2010	Financial loss more than $400 Million Yen	51,52
Shanghai Apartment Fire	China	2010	58 Fatalities and 71 injuries	53,54
Wanxin Complex Fire	China	2011	No casualties	54,55
Tecom Building Fire	Dubai	2012	2 Injuries	56
Tamweel Tower Fire	Dubai	2012	Repair works have begun after 3 years	57
Mermoz Tower	France	2012	1 Fatality, 6 injuries	58
Lacrosse Building Fire	Melbourne, Australia	2014	No casualties	59,60
The Torch	Dubai	2015	Large quantities of burning material fell	61,62
The Address	Dubai	2016	15 injuries	63,64
Grenfall Tower	UK	2017	80 fatalities, 70 injuries	65-68
Neo 200 Building	Melbourne, Australia	2019	1 injury	69,70

insulation had greatly contributed to the rate of propagation; the entire façade of the building was engulfed in flames within 14 minutes.[54]

According to the Council on Tall Buildings and Urban Habitat,[71] the global annual skyscraper completions after 2010 was generally greater than 70 completions, annually more than 100 completion after 2014. A series of skyscraper fire incidents involving cladding materials occurred after 2010,[56-58,61-64] which had revealed the difficulty to extinguish and control while cladding fires took place in skyscrapers; the higher location of the cladding fire would introduce a higher amount of oxygen and wind into the fire and contribute into a higher rate of fire propagation. Moreover, the difficulty to conduct exterior fire suppression would also be raised with the height of the building due to the limitation of water supply and other physical restrictions. In some cases, fire-fighters had to climb the stairs to extinguish the fire from the inside since they were unable to extinguish the fire from the exterior of the building.[70]

Unfortunately, skyscrapers fires continuously occurred within a relatively short time period in 2015 to 2016,[62] including a 79-storey "The Torch" and 63-storey "The Address" in Dubai. For "The Torch" fire in 2015, more than 40 floors were burning on one side of the building. This also caused large quantities of burning debris to fell from the higher level which started a secondary fire at the lower levels.[61] The burning debris was also carried by the strong wind and littered around the surrounding streets (Figure 4). This was particularly hazardous for the densely populated Dubai. The Address is another skyscraper fire that occurred in Dubai in 2015. Fortunately, there were no deaths and only 15 injuries.[63,64] The rapid fire propagation across the building was attributed to the cladding materials used, which were made of aluminum composite panels with a polyethene core. The ensuing rapid vertical fire spread considerably reduced the time for occupants to evacuate and fire fighters to operate.

2.2 | Cavities

In order to enhance the insulation efficiency of the cladding system, cavities are frequently included between the panels and the cores. While the flame from the incidents invades the cavities, the flame length is able to stretch up to 5 to 10 times as the fire travels to consume oxygen for combustion. Although the lesson from UK Knowsley Heights Fire in 1991 had introduced a new regulation for horizontal cavity barriers at each floor,[40] cavities could still be formed by structural displacement or the melting of the insulation and core material.[48,50,58] This phenomenon could result in tremendous consequences; as the fire is unseen within the cavities, fire fighters or evacuators could be misled on risk judgment in a certain area. In the Australia Tip Top Bakery Fire in 2002, fire fighters switched to defensive firefighting from internal offensive firefighting strategy after the structural collapse of the expanded polystyrene sandwich panels were observed.[43] The USA water club tower fire incidents in 2007 had also revealed the vertical flame stretch through the cavities between the panels.[44] The fire spread vertically and rapidly reached the top of the 41 stories high building on one side the building. Consequentially, a

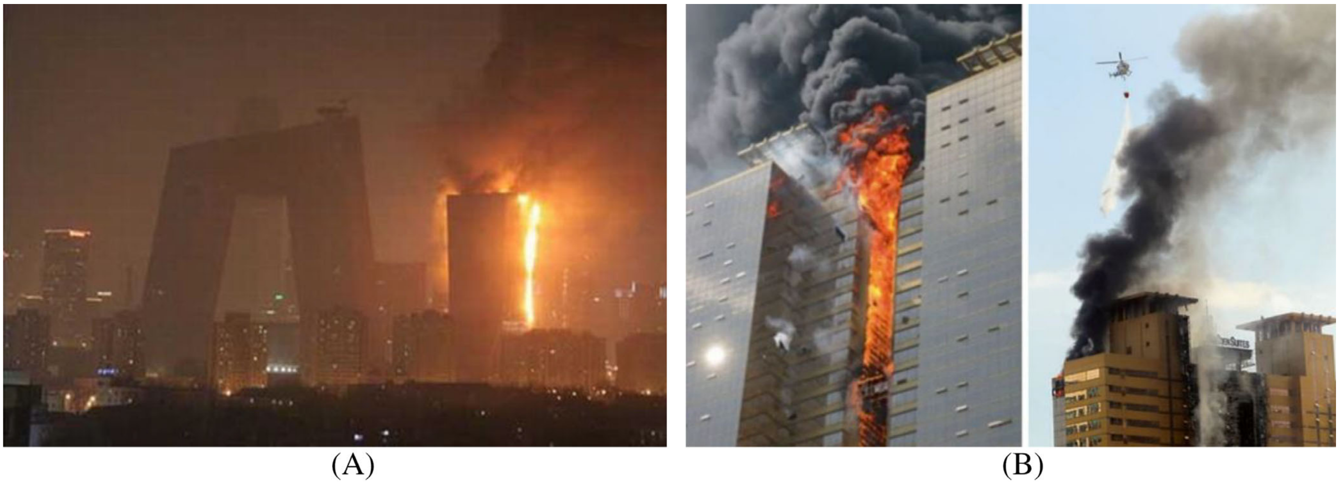


FIGURE 3 (A) Incident at the new CCTV tower on fire[50] and (B) Wooshin Golden Suites, Busan South Korea[51]

significant amount of falling structural debris occurred within about a quarter mile of the building.

The Wanxin Complex fire in China had illustrated a more significant example of the fire risks on cavities. The façade of the building comprised of aluminum composite panels, expanded polystyrene foam for insulation and the air cavity between the cladding and insulation was reported to range from 160 to 600 mm.[54] After the insulation was ignited by the fire source, high temperatures resulted in the decomposition of the aluminum composite panels; more insulation materials were exposed to the fire. Eventually, the fire penetrated the aluminum cladding and spread onto the extruded polystyrene insulation, the fire engulfed the entire south façade within 20 minutes.[55]

2.3 | Fire re-entry

When the fire rapidly spread along the cladding surface and cavities, windows or other openings of the building would allow the fire to propagate back into the building. From the reviewed cases, it can be observed that the fire re-entry phenomenon could easily create a secondary fire source on multiple floors. The consequences of the fire re-entry could be catastrophic, as secondary fire source would invade the area which was determined as a safe area by fire fighters or evacuators previously and also obstruct the evacuation pathway for some occupants. A cladding fire occurred at the 32-story Monte Carlo Hotel and Casino in 2008. The exterior cladding materials were first ignited on the left side of the central core area, propagated along the cladding surface and travelled to the left and downward. It can be observed that the heat from the exterior fire had broken several windows and trigger the fire re-entry phenomenon. Fortunately, the internal sprinklers halted any fire spread into the interior guest rooms.[45,46]

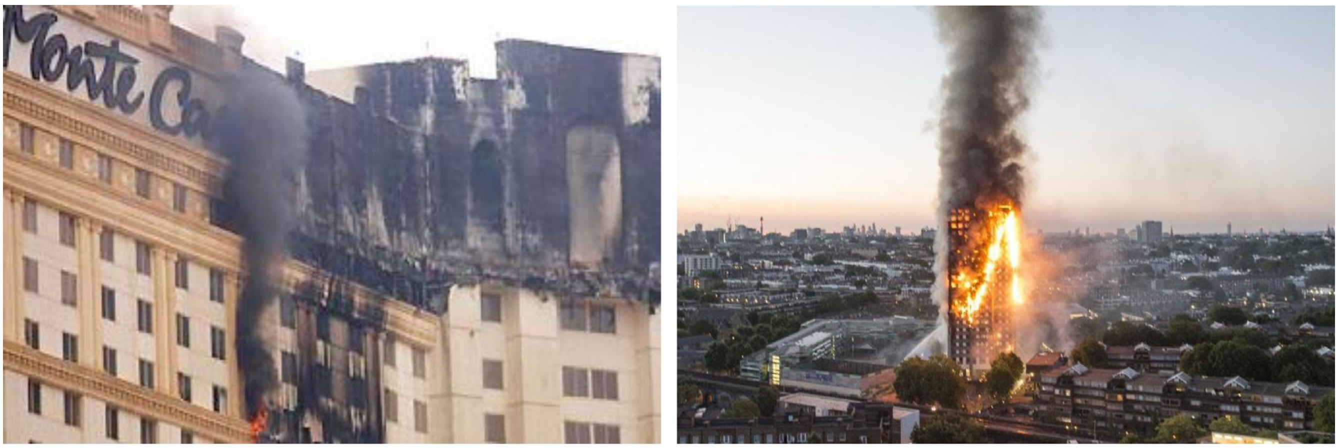
Such phenomenon also appeared in the infamous Grenfell Tower fire incidents in 2017, shown in Figure 5B, which had tragically resulted in 72 deaths and 70 injuries during the fire incidents. The rapid-fire propagation was ascribed to the cladding materials, which were the aluminum composite panel with a polyethylene core and polyisocyanurate thermal insulation.[66,67] Although the ignition source in the fourth floor kitchen had been suppressed by the fire fighters with quick responses, the fire eventually spread onto the exterior cladding. The flames propagate expeditiously along with the exterior cladding and re-entered the building on multiple floors. Therefore, trapping a significant percentage of residents inside the building, the occupants were unable to evacuate and resulted in the tremendous 80 deaths.[65]

2.4 | Abstract

In summary, significant fire cases from 1990 to 2019 are presented chronologically in Figure 6. For the 1990s, although external cladding was mainly applied for industrial or specific buildings previously, the cladding system began to be installed for a residential and commercial building in early 1990s, as the characteristics of ACP provided a cost-efficient and architectural improved option for developers and engineers. After 2000, the successful early application of the external cladding system in the 90s has proven the advantages and superiority of the external cladding system for residential and commercial buildings. The rapid increment in external cladding application had resulted in a raised in cladding fire incidents, the number of global annual cladding fires was averagely five incidents from the early 2010s, which is a 600% increment along the decades.[12] However, at the same time, due to the lack of fire safety regulation for cladding system, especially for skyscrapers, the skyscrapers annual completion from 1960 is illustrated in Figure 7, the numbers of skyscrapers were rapidly built after 2010, which also leads to a significant increase in cladding fires occurring on skyscrapers after 2010. The identification of cladding fire risk is vital to improve the fire safety of exterior wall claddings. In this section, the major fire risks were identified through reviewing the significant fire cases in the past decades, which are (a) rapid surface propagation; (b) cavities; and (c) fire re-entry.

(A) (B)

FIGURE 4 Images of the Torch fire on (A) the building and (B) smaller fires caused from falling debris[61]



(A) (B)

FIGURE 5 (A) MGM Montecarlo Hotel fire[47] and (B) the Grenfell Tower fire[68]

3 | POTENTIAL FIRE RISKS OF CLADDINGS SYSTEM

Owing to the nature of core material applied within the façade system, once the flame impinges upon the exterior wall, there is potential for the fire to intensify and spread along the building surface. Three primary fire propagate means are observed based on previous fire incidents review: (a) Exterior fires spread along the surface of the cladding system, (b) fires propagate through existing voids between the edge of the floor and the building façade due to inadequate fire stopping, (c) fires re-entry through a window-to-window mechanism that flames discharge from a fire billowing out of the broken window, climb up through exterior building façade, and then ignite flammable material located in the upper floor. The postinvestigation performed after these fire events exhibit that the potential fire risks are strongly correlated to the material presented in the cladding. Particularly, the risks boost when noncompliant ACP products were adopted. To have a thorough understanding of fire behavior of façade system and emphasize how this vulnerability building facade system influences the safety of building residents, this section provides a comprehensive elucidation of the cladding system and the effect of cladding material. Furthermore, the possible fire risks that relate to the external façade system are introduced in detail.

Through our study, the majority of high-rise building fires involve the burning of ACPs. This includes local fire incidents in Australia, as well as international fire incidents such as the Grenfell Tower fire, U.K., in 2017. ACPs are constructed using a thin layer of aluminum, covering a high-density polyethylene polymer core.[72,73] The core of the sandwich cladding structure is extremely flammable due to the nature of the material used. When ignited, the melting and dripping effect are often found to promote fire propagation vertically across building levels, significantly reducing the amount of time for safe egress, and difficulties for fire fighters to enter the building to fight the fire or rescue trapped occupants. The major risks of noncompliant buildings can be divided into the following three categories, as depicted in Figure 8.

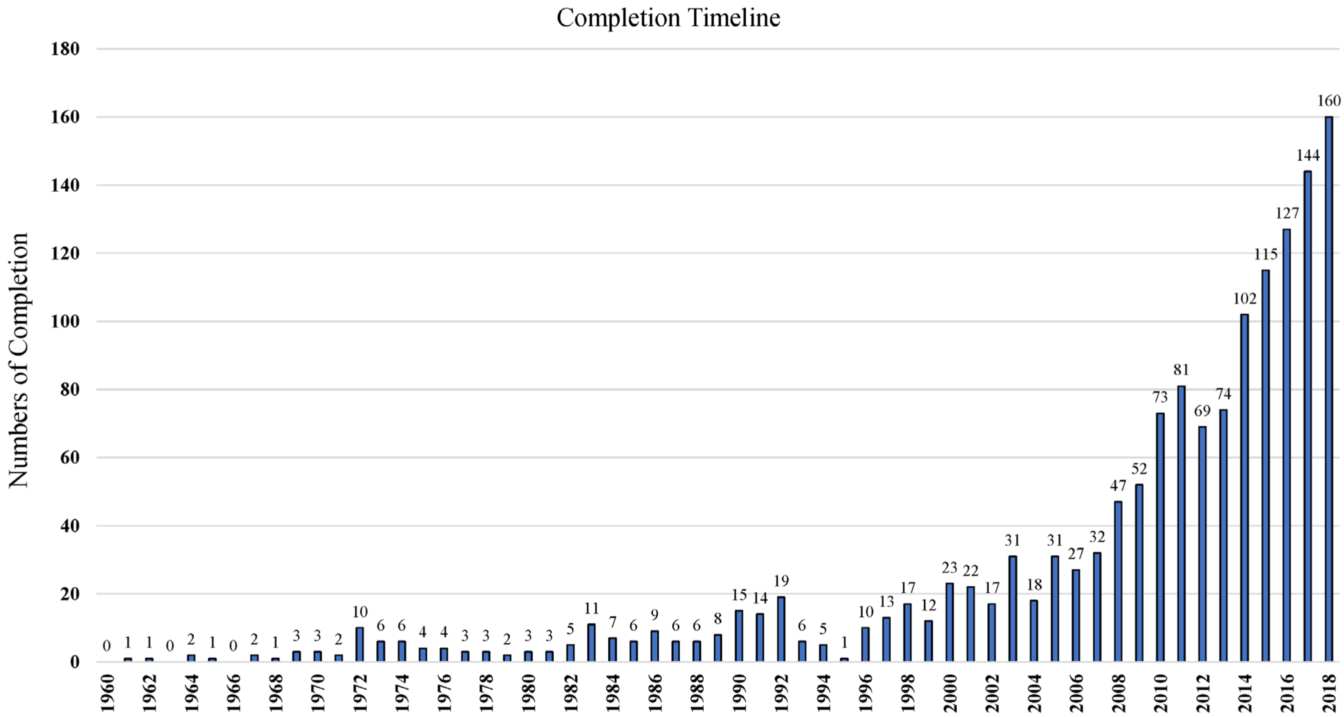


FIGURE 6 Summary of the recent cladding fires

The potential risks associated with the noncompliant building structures can be realized by exploring the three mechanisms to link with possible hazards, which have been reported from previous fire investigative studies. In summary, the following are the identified potential risks that will likely to occur during a fire involving external noncompliant building panels.

3.1 | Rapid vertical fire propagation

While the core of the aluminum composite panels is mainly comprised of highly combustible polymers, once they are ignited, the fire will rapidly spread across the panel in a short period.[74] This greatly increases the difficulty of fire evacuation and firefighting operation tactics. Furthermore, the prediction and decision made by the first respondent will be critical in the event of cladding fires.

3.2 | Evacuation difficulties for multiple floors

In cosmopolitan cities, aluminum composite panels can be commonly found in high-rise commercial and residential buildings. In the event of external wall fire, fire may occur on multiple floors due to the fire re-entry phenomenon.[54] Fires occurring in different vertical locations may trap the occupants within the building, causing it extremely difficult to evacuate. This will also greatly increase the risks of rescuing the occupants within. It is also identified as one of the major causes of casualties in this type of fire.

3.3 | Immobile occupants evacuation issues

Followed by point (b), the outbreak of multiple floor fires will lead to additional challenges for immobile occupants such as the elderly, disable, and children, to evacuate from the building effectively.[75-78] In addition, the rapid vertical fire spread will shorten the safety egress time.

3.4 | Internal fire expansions on multiple levels

Cavities are often included in aluminum cladding panel systems as they can improve thermal insulation. Nevertheless, when a fire occurs within these cavities, it will create a suction effect causing the flame to stretch within the composite hidden cores internally. This may also contribute to the fire size and toxicity releases that can be extremely hazardous for fire fighters.[79-81] It can also lead to possible instantaneous flashovers.

3.5 | Difficulty for aerial fire-fighting operations

In the event of external wall fire, the entire building can be covered by fire on the surface, which greatly increases the degree of difficulty of firefighting and rescuing of occupants via aerial operations. Moreover, it will also be difficult to perform aerial applications on the roof of the building due to rapid vertical fire spread and buoyant hot plume behaviors.[82,83]

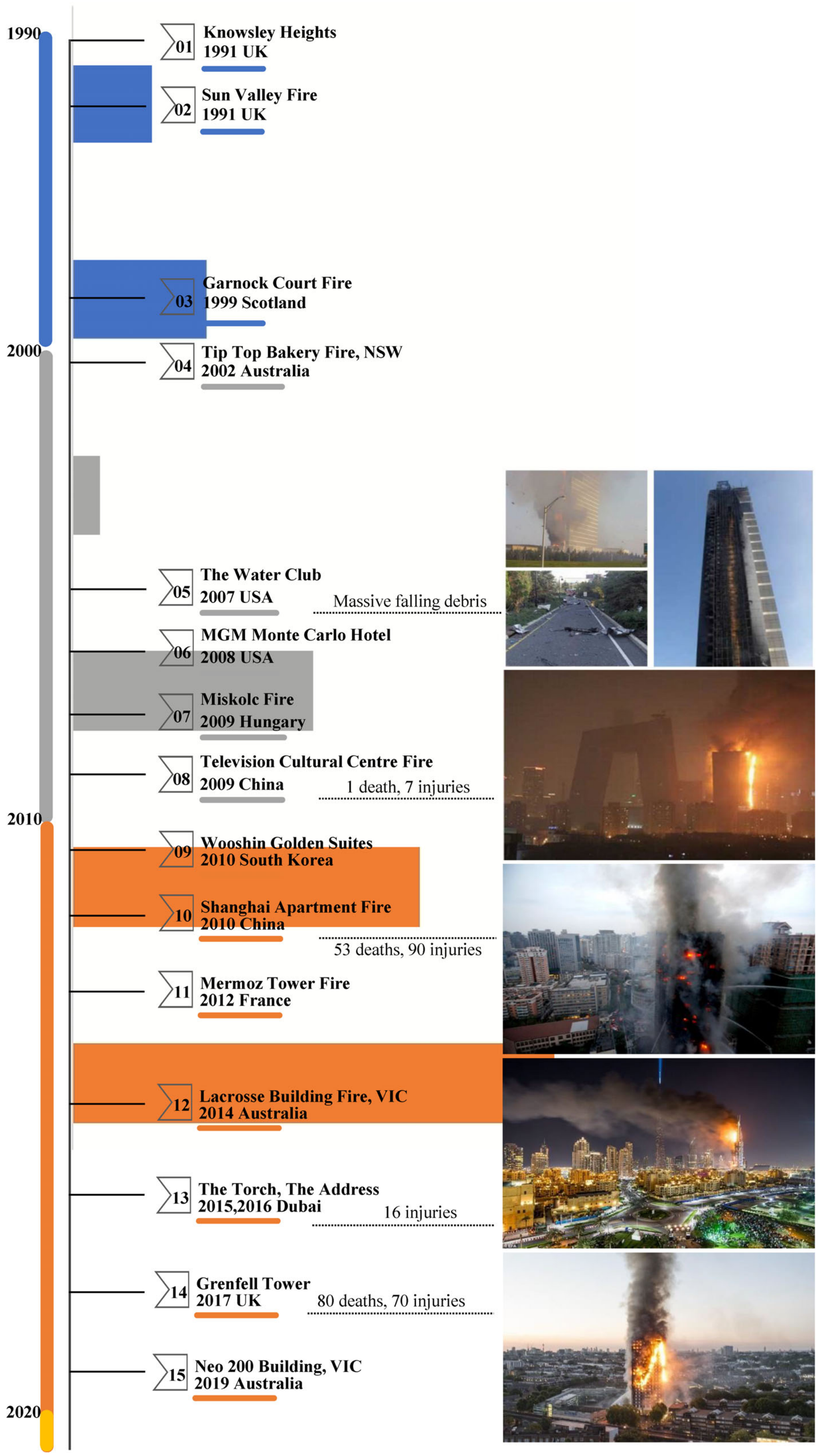


FIGURE 7 Completions of skyscrapers[71]

3.6 | Ineffectiveness of building sprinkler and hydrant systems

The intensity of cladding fires will exceed the limits of the building fire suppression systems (ie, sprinklers and hydrants).[84-86] The design of these systems may not account for the overwhelming fire development due to the rapid spread of the external cladding system. The existing sprinkler system may not be effective in controlling such fire as they are normally installed internally to serve the building compartmentally.

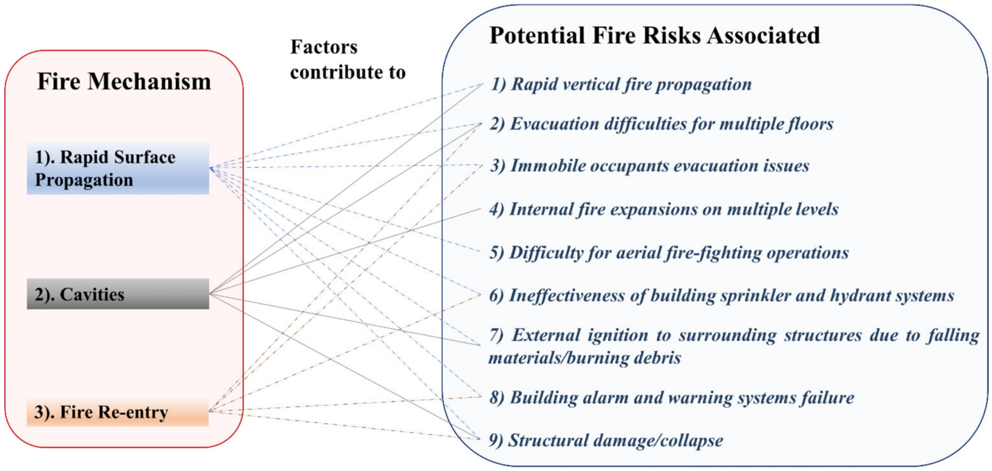


FIGURE 8 Relationship between fire mechanism and fire risks

3.7 | External ignition to surrounding structures due to falling materials/burning debris

The external cladding system normally comprises of multiple layer material components, which may be influenced by the melting and dripping effect. Falling materials or burning debris owing to rapid delamination of the cladding layers poses a significant hazard to the surrounding infrastructure and pedestrians.[87,88]

3.8 | Building alarm and warning systems failure

In general, building fire detection and alerting systems are installed internally on the ceiling of each compartment. In the case of a fire outbreak externally on the cladding panel system, the failure or significant delay in the evacuation alarm and warning system may greatly increase the responding and early egress time for building occupants.[89-91]

3.9 | Structural damage/collapse

In rare cases of high severity cladding fires, the overwhelming intensity of the flame can cause significant structural movements. When the building supports are compromised by the severe fires, partial or full structural collapse of the building structure may occur.[51,92-94]

3.10 | Abstract

In short, the aforementioned potential risks can be attributed to the three major fire spread mechanisms of the external cladding panel system. These potential outcomes are highly correlated to the type of building materials applied within the cladding composite system; in particular, the risk increases substantially for those who are installed with noncompliant building products. Therefore, this highlights the need for establishing a systematic procedure for compliance check of these materials in case of the three major fire spread mechanisms. While a new standardized experimental fire test method can be created to tackle this issue, preliminary investigation is required on the key parameters to classify the pass/fail criteria of building structure installed with a cladding panel system. Recently catastrophic incidents have forewarned the company and government to draw attention to understand different façade properties, especially its flammability. Currently, the government has established cladding taskforce to investigate the fire safety issues associated with noncompliant cladding products and buildings.

4 | CURRENT CLADDING REGULATIONS AND TASKFORCES

There has been consistent rectification of the relevant building regulations in various jurisdiction worldwide.[95-98] In the Australian context, the Lacrosse Building fire and the Grenfell Tower Fire have highlighted the need for regulatory reforms regarding flammable cladding material. Concerns have also been raised about other potentially flammable building materials.

4.1 | Provisional regulations on claddings

In June 2017, a Senate committee was established to investigate the use of cladding materials on Australian buildings in the aftermath of the deadly Grenfell tower fire.[99] The committee identified a range of key issues that have contributed to the issue of noncompliance and nonconformity in building products in Australia. These include (a) increase in products imported from overseas—there is a massive increase in materials coming from off-shore manufacturers, creating issues in third-party certification schemes and their reliability; (b) reliability of certification documentation—there is an increase in cases of fraudulent or misleading material compliance documents, which leads to noncompliant materials being used on building construction; (c) inappropriate product substitution—the aggressive cost-cutting in construction which often leads to substituting for inferior products that underperform compared to original specifications. (d) Clarity of material Certification for Conformity—there is a lack of clarity in building codes in relation to flammable cladding material. This inconsistency has decreased confidence in certificates of conformity that have been issued under the Australian Building Codes (BCA).

Based on the four key issues, a process was proposed to manage the problem in four phases,[100] which are data capture of potentially affected buildings, scoping impacted buildings, assessing the risk to the community, and ensuring consistency in safety outcomes. Essentially, the process presents an identification, assessment, and remediation workflow to deal with noncompliant aluminum cladding. The procedure begins with: (a) Data audit to identify buildings containing combustible aluminum cladding. (b) Information and notice are then given to the owners and managers of the buildings identified in the audit. This can also include recommendations to check approvals and conduct fire safety assessments immediately. (c) The taskforce will also undertake routine checks and require the owners to report back on the cladding on the residential buildings. With the urgent need to resolve the present fire risks of existing building products and develop economically viable solutions, it is paramount that an assessment tool is developed to evaluate underlying risks for existing and ongoing development of responses to noncompliant materials on buildings. A deeper understanding of the associated risks is not only beneficial to the building occupants but also to frontline responders, who risk their lives during their response to fire events such as Grenfell Tower.

4.2 | Australian cladding taskforces

In the context of fire induced by building materials, especially cladding in Australia, some efforts were made by cladding taskforces assembled from different states, triggered by the Grenfell Tower fire in June 2017, in order to ensure that fire safety requirements for external wall cladding were prioritized and adequately addressed. The cladding taskforces from each state released statistics of their audit for noncompliant building materials. Unfortunately, relevant legislation and building codes have yet to catch up with the requirements for assessing the fire risks involved in these buildings. There remains a lack of clarity in the National Construction Code for flammable cladding material.[101] Prior to a government inquiry, there are no existing fire safety regulations in Australia to promote the safe use of lightweight materials for external façades. Authorities have further proposed that the taskforces should undertake product testing on commonly available external cladding products with the subsequent development of a materials library which would allow a rapid assessment and product classification for samples taken from government and private buildings. Following the government inquiry, an interagency Fire Safety and External Wall Cladding Taskforce was established in all the states to ensure that fire safety requirements for external wall cladding were prioritized and adequately addressed. The taskforces research work from New South Wales (NSW), Victoria (VIC), and Queensland (QLD) is summarized here.

The main objective of NSW Cladding Taskforce was to detect buildings with potentially combustible cladding, as well as support local city councils to address the use of existing noncompliant cladding materials. To date, the taskforce has audited 185 000 buildings, in which 4127 buildings have already been inspected by Fire & Rescue NSW (FRNSW). Thousand one hundred and eighty four (1184) buildings were identified to have aluminum cladding. The Taskforce proposes to visit each of those buildings and has already identified 220 buildings, including 58 high-rise residential buildings necessitating further investigation.[102] Similar data have also been reported in all the other states. Apart from this, more than 62 000 letters were sent out by the taskforce to building owners, residents, and local councils, informing them about the assessment of claddings and ways of reducing fire risks on noncompliant cladding materials.

The VIC Cladding Taskforce established by the Victorian state government intends to investigate the extent of noncompliant external wall cladding on state-wide buildings and make recommendations for improvements. In 2017, systems failures and wildly employed noncompliant combustible claddings in the building industry across the state had been identified to be a major contributor to safety risks.[103] The taskforce continues on policy reforms to ensure Victorian buildings are safe and comply with the law in the next year.[104] The VIC Cladding Taskforce has managed to make significant strides identifying buildings with cladding, notifying, and training crews. For example, one of the most significant developments of the taskforce is the reaction to the Neo200 building cladding fire, which was occurred at 182 to 200 Spencer Street, Melbourne, on February 4, 2019. Metropolitan Fire Brigade (MFB) was able to extinguish the fire quickly. 371 apartments were evacuated, and there were no deaths or serious injuries.

The QLD Government established Non-Conforming Building Products (NCBP) Audit Taskforce to conduct a targeted investigation into buildings using ACP cladding and other possible combustible products in 2017.[105] According to the 2018 Taskforce Status report, over 27 000 approvals had been reviewed and excluded from a further investigation.[100] The report also indicated that the application of combustible thermoplastic material (ie, PE) sandwiched between aluminum panels would contribute to fire spread, considering that the degradation of materials in a fire would result in dripping of burning debris, pooling, or detaching while flaming onto lower areas which may cause further fire spreading. Moreover, in cooperation with the University of Queensland (UQ), a material library was built, containing fire behavior of numerous cladding composites, insulation materials. This material library is a tool to deliver the data required for qualified fire safety engineers to perform the analysis necessary to determine the safety of a façade system analogous to a particular group of materials, compositions, and other building contexts.

4.3 | Review of fire test method

A fire test is required to understand the behavior of structures exposed to fire and is a means of determining whether fire protection products meet minimum performance criteria as set out in a building code or other applicable legislation.[106] There are many different types of fire tests apart from those on firestops. Also, the range of tests is based on different major objectives and equipment, such as fire resistance of various elements of construction, spread of flame tests on building materials, smoke developed or emitted tests on building materials, rate of heat release, and so on. This section reviews the current fire test methods on external cladding panels, which includes different scales of façade tests and the Australian fire propagation test method.

4.3.1 | Full scale Façade tests—BS8414-1

BS 8414-1[107] is a full-scale fire test for non-load-bearing external cladding systems applied to the face of a solid external building wall (Figure 9). The test simulates the scenario of flames emerging from a compartment fire via a window at the base of the wall. BS 8414-1 is well-recognized in UK, China, Japan, and the United Arab Emirates.[98] The test façade is configured according to the dimensions above with an expected heat output for the crib of 4500 MJ over 30 minutes to achieve the following exposure: (a) The mean temperature across the top of the combustion chamber opening measured at three thermocouple locations exceeds 600°C above ambient over a continuous 20 minutes period. (b) The mean temperature at level 1 height on the main wall face exceeds 500°C above ambient over a continuous 20 minutes period.

The performance criteria for this standard is (a) The fire spread start time is defined as the time when the temperature measured by any external thermocouple at level 1 exceeds 200°C above ambient; (b) failure due to external fire spread is determined when any external thermocouple at level 2 exceeds 600°C above ambient for a period of at least 30 seconds, within 15 minutes of the fire spread start time; (c) failure due to internal fire spread is determined when any internal thermocouple at level 2 exceeds 600°C above ambient for a period of at least 30 seconds, within 15 minutes of the fire spread start time. There are also some other related testing standards for the main full-scale fire test methods worldwide, such as ISO 13785-2,[108] NFPA 285,[109] SP Fire 105,[110] ANSI FM 4880,[111] and so force.

4.3.2 | Intermediate scale Facade test—ISO 13785:2002 Part 1

The test façade is installed as a re-entrant corner "L" arrangement with a total specimen height of 2.4 m, such size is nearly one of a third of the size of BS8414-1. The fire source is a linear propane burner with dimensions 1.2 m × 0.1 m, located 0.25 m below the bottom edge of the rear wall. The burner has a constant 100 kW output which is sufficient to achieve direct flame impingement on the bottom 200 mm of the rear wall façade. For the intermediate scale test, vertical channel test[112,113] and FM parallel panel test[114,115] have been also used.

4.3.3 | Small-scale tests

Combustibility tests are essentially used to determine if materials are combustible or noncombustible for small-scale tests. Various standard test methods exist around the world including (ISO 1182,[116] BS 476 part 4,[117] ASTM E136,[118] ASTM E2652,[119] AS 1530.1[120]). Small specimens are exposed to high temperatures of typically 750°C or 835°C within a small conical tube furnace. Criteria for noncombustibility are typical including (a) no sustained flaming (typically >5 seconds); (b) mean furnace temperature rise must not typically exceed 50°C; (c) mean specimen surface temperature must not typically exceed 50°C; and (d) criteria for limited specimen mass loss may also be applied. Many building codes around the world consider materials such as gypsum plaster to be noncombustible. External wall assemblies constructed entirely of noncombustible materials do not generally pose any hazard relating to fire spread. Except the combustibility test, small-scale tests also include other test methods, such as cone calorimeter test and flame screening test.

4.3.4 | Fire propagation testing and classification of external walls of buildings in Australia—AS 5113

Currently in Australia, builders and land developers refer to AS 5113[121] for any external wall installations for compliance to fire safety performances. The main purpose of the AS 5113 is listed: (a) Identifying the performance of external (combustible) wall systems through a collective procedure of guidelines; (b) previously façade testing was not in common use in Australia. Fire engineers were often required to assess subjectively the overall external wall fire performance, based on "fire hazard" tests alone, or noncombustibility testing for small parts of external wall systems; (c) provide details on the test procedures for the fire performance of external walls including wall fire spread and building to building fire spread; (d) provides an alternative solution for compliance check of combustible façade materials.

In the latest up-to-date issue (2016), AS 5113 standard provides a set of procedures and criteria for the classification of external walls of buildings to their tendency to spread fire, which includes: (a) via the external wall; (b) between adjacent buildings; and (c) production of falling debris which may lead to danger to evacuating occupants and fire fighters. AS 5113 is applicable to all external vertical or near vertical surfaces and covers all types of external wall systems (ie, facades, outer skins, core materials, cavities, and attachments). This standard applies the definitions in ISO 13943, AS 2484.1 and the test procedure for wall elements exposed to radiant heat using a 3 m × 3 m furnace. Australia has amended fire test methods and regulation to enhance the fire safety of the façade system,[5] but the challenge of ensuring compliance still exists.

5 | RESEARCH WORK ON CLADDING FIRES

In this section, academic research studies on cladding fires through both experimental and numerical approaches have been extensively reviewed. The aim is to provide insight into the latest research and knowledge gap in terms of the understanding of the cladding fire mechanisms and combustibility of existing ACP composites. Recent advancement in experimental and numerical studies have been summarized and discussed to identify the critical issues and concerns for current ACP products.

5.1 | Experimental study

Fire safety and protection systems are still mainly based on prescriptive codes (ie, the Building Code of Australia (BCA) for fire protection in buildings) which are based on experimental fire testing. Therefore, the majority of cladding fire research is through experimental approaches. Cladding fires are complex in nature, as multiple factors such as cavity depth, core materials, and environmental conditions can significantly affect the fire spread behavior. Many researchers dedicate their effort to focusing on different aspects of cladding fire.[122-127] In this section, we summarized the typical experimental studies on the cladding systems in the latest decade.

One of the earliest work on cladding panel fires is carried out by Yoshioka et al, in which a study of a test method in the form that flame blown from the aperture (910 mm square) roasts the façade-type test body (4095 mm high × 1820 mm wide) in 2011. It aimed to evaluate the fire propagation of the exterior thermal insulation method installed on the outside of the exterior façade walls which have the fire-resistive construction.[128] In 2014, they investigated the amount of heat release of combustible façade specimens compared with blank testing, an increase was found and that reflected the combustion of inflammable materials applied within facades, surface temperature, time-temperature area, incident heat flux during fire test should also be considered to evaluate the fire propagation over combustible façades.[129] Façade fire tests were conducted by Nishio et al in 2013 on specimens of various combustible exterior wall, such as wood, sandwich panel, photovoltaic sheet mounted on composite panel, combustible coating material, and exterior thermal insulation with vent layer.[130] In 2016, the tentative criteria of a fire spreading to an upper floor were determined by the same group based on the time taken to reach 500°C and duration of temperature exceeding 500°C on a facade surface when examining a vertical fire spread along the facade. Compared to the real fire, the calibration test showed a higher value of opposite-surface incident heat flux, which could be applied to evaluate the influence of fire spreading to an adjacent building via a combustible façade.[131]

The cladding panel fire tests become more systematic and standardized during the late 2010s. In 2016, Jamison et al developed a test protocol for the incorporation of cavity walls into FM Approvals Standard for Cavity Walls and Rainscreens, and Class Number 4411 has been presented and validated. The exposure fires of 5.8 kW in the 51mmwide cavity test and 9.5 kW in the 102mmwide cavity test provide appropriate thermal insulation to the samples in order to make a judgment of acceptable performance.[132] Lalu et al found that 50 cm width of noncombustible fire barriers, vertically measured, is adequate in terms of fire safety and economic in terms of optimization of the global system of noncombustible fire barriers. This proposed size reduces technological materials losses by 40% and eliminates potential installation errors due to material continuity.[133] Furthermore, Hajdukovic´ et al conducted fire experiments on two two-storey large-scale facade samples with the same overall geometrical and material details. The incident heat flux (IHFFS) upon the surface of the facade and damage of the facade's thermal strain has been investigated.[134] Through the experiment results, it was concluded that the problem of flame propagation across a thin-rendered EPS external thermal insulation composite system facade was not exclusively a problem of the applied materials but was closely connected to the facade shape. In 2018, a façade fire propagation test was conducted by Guillaume et al according to the ISO 13785-1 standard, with additional heat release rate and gases analysis using FTIR.[135] Through nine different compositions of aluminum composite panels (ACM) tests, ACM-PE-based cladding systems gave very different results from the other solutions tested, especially on the heat release rates. Also, ACM-FR and ACM-A2 claddings showed a similar manner in the fire test.

To further improve the understanding the hazardous level of the polyethylene-based ACP external façade system, an experiment was conducted by Srivastava et al on a full-scale three-storey building with firestops, ACP, and glass windows.[136] The façade testing structure was designed to study two specific fire propagation phenomena involving the local fire development within the external wall system and the involvement of fire entry toward the building interior. Reinforced glass panels with a dimension of 1200 m × 400 m were installed in the experiment. Since 6 mm thickness of the external façade system has been widely applied in low- to mid-rise structures, an exterior wall with 6 mm thick comprised of ACP sheets (1200 mm × 400 mm × 4 mm) made by 3.5 mm thick low-density polyethylene cores was considered in this study. To obtain the pyrolysis behavior of low-density polyethylene, as a reference, thermal gravimetry analysis was conducted with four different heating rates using a temperature range from 25°C to 540°C in nitrogen condition. It is notable that the solid decomposition occurs in the temperature range of 300°C to 450°C.

Figure 10 illustrates the burning behaviors of Test A. Figure 10A indicates the ignition point of the external wall (ie, time considered as 0 mins). After 4:03 minutes, the fire spread to the first-floor façade as shown in Figure 10B. It is notable in Figure 10C that the bulk ground floor façade has collapsed. At 5:38 minutes, the fire grows on the first floor due to the façade collapse providing greater ventilation (see Figure 10D). As the entire ground floor is burnt out as seen in Figure 10E, the fire continues to propagate to the second floor after 19:38 minutes (see Figure 10F). Also, in this study, the leap-frog effect, which is a window-to-window mechanism where combustible materials behind an upper window are ignited by the intense radiation, is observed. This phenomenon depicts significant fire exposure. When the intensities of flame and hot gasses escaping through a

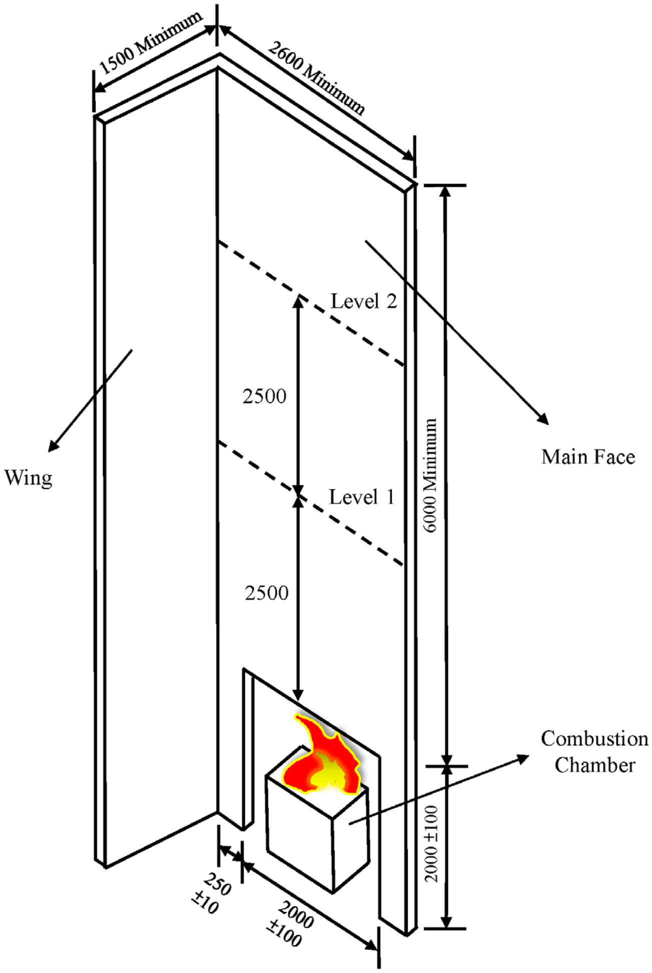


FIGURE 9 Illustration of BS 8414-1 full-scale façade test[107]

lower window opening, the aggregated radiation heat is sufficient to trigger fire re-entry or rapid vertical fire spread behaviors. As a consequence, the fire spread vertically at the exterior of the building, circumventing the interior perimeter fire barriers, any inherent fire resistance of the exterior wall assembly and sprinkler system. When the leap-frog effect occurs on a given floor, there is a high possibility where the same fire propagation effect will occur and spread to every floor on top of the fire origin.[137]

Through this full-scale experimental study, the various stages of the external cladding wall fires have been reviewed. This involved multiple fire behaviors including the heat penetration into the core of the façade system; ignition and fire growth of the combustible core of the ACPs; rapid fire development due to the increase in surface contact area for ventilation; and falling debris and secondary ignition to other building materials. This experimental observation provides us with further insights into the possible hazards of fires derived from ACPs. In summary, the reviewed research works have highlighted the combined efforts of fire researchers on the issue of cladding fires. Furthermore, it provides a solid foundation for the development of future testing standards and compliance for combustible cladding systems.

5.1.1 | Bench-scale study of ACP products

Traditionally, sandwiched panels are widely applied in aerospace and marine applications. In recent times, they have been utilized increasingly as building façade construction to provide an envelope to the building for thermal insulation, weather resistance, as well as enhance the aesthetics of the building. ACPs are manufactured with numerous types of core materials ranging from the highly combustible such as polyethylene, polyurethane, and polystyrene to noncombustible such as mineral wool. The major fire risks of ACPs are primarily due to the internal combustion of the system, which is governed by the core material. The different types of existing ACPs on buildings and their combustibility characteristics have been list as follow: (a) PE cores: Regarding the European fire test EN1350.1, the existing ACP products with PE core is classified into three categories based on the proportion of PE. As ACP products contain lower than 30% of PE, such composite products labelled as "A2." When the amount of PE is approximately 30%, such composite panel labeled as "FR" (fire retardant). However, when the percentage of PE is higher than 30% which is considered as highly flammable and is prohibited to be applied to building façade system. (b) Fire-retardant (or FR) cores: Fire-retardant core is made up of a greater percentage of fire-retardant mineral wool with the balance being PE. Noncombustible insulation materials have a very limited contribution to fire since they are difficult to ignite as well as the minimal spread of flame. This type of panel is acceptable for use on high-rise buildings. It is required to attach to a fire-rated wall. (iii) Aluminum cores: The core is constructed from a solid aluminum structure. Also, there are panels made of an aluminum foil honeycomb structure. It is deemed noncombustible EN1350.1: A1 low potential to spread the fire. This type of panel is acceptable for use on high-rise constructions. It must be attached to a fire-rated wall.

The University of Queensland has established an elementary database of cladding materials applied in buildings. Table 2 summarizes cone material of ACP products under the cone calorimetry (ISO5660) under three different sets of radiation heat fluxes.[138] The cone calorimeter is a standardized bench-scale apparatus that is widely employed and accepted globally to determine fire performances of material composites. It is designed as a cone-shaped heater where specimens are placed under the heating coils with the cone shell. The experiment can be run by user-specified heat fluxes typically ranging from 0 to 80 kW/m^2. The cone calorimeter portrays a well-defined fire scenario, then thoroughly characterizes the fire properties such as heat release rate, time to ignition, and mass loss rate.

Figure 11 demonstrates the flammability of various ACP products under different heat flux introduced, which were 35, 50, and 60 kW/m^2. Notably, the relationship between time to ignition and the peak heat release rate is a negative nonlinear relationship. In most of the cases, with an increment of the heat flux, the time required to ignition significantly reduces. Furthermore, in general for all the ACPs, increasing the heat flux from 35 to 50 kW/m^2 will result in the reduction of ignition time by half approximately. On the other hand, a further increment of the heat flux after 50 kW/m^2 does not significantly change the ignition time. Therefore, it is notable that the common

(A) 00:00 minutes (B) 04:03 minutes (C) 04:47 minutes (D) 05:38 minutes (E) 17:30 minutes (F) 19:38 minutes

FIGURE 10 Images extracted from various time instances of the fire test video footage[136]

TABLE 2 Cone calorimeter testing results of commonly used ACP products (data extracted from UQ database[138])

Material ID	ACP 01	ACP 02	ACP 03	ACP 04
Core material	Predominantly inorganic core	Ethylene-vinyl acetate (EVA) and a fire-retardant core	Polyethylene (PE) core	Predominantly organic composition rich in aromatics, such as cellulose-based and/or phenolic polymers

Material ID	ACP 05	ACP 06-S1	ACP 07	ACP 09
Core material	Polyethylene modified with vinyl acetate (PE-VA) and a fire-retardant core	egg-box core with polymer adhesive on both sides—S1—profiled side	Polyethylene (PE) and an inorganic filler core	Polyethylene (PE) modified with vinyl acetate (VA) and a fire-retardant core

Material ID	ACP 10	ACP 11
Core material	Aluminum foil honeycomb structure connected with a polyurethane-based adhesive containing an inorganic filler	Polyethylene (PE) and a fire-retardant core

ACPs is capable of withstanding external radiation heat fluxes up to approximately 35 kW/m^2, for at least more than a minute.

The cone calorimeter results show the combustibility and flammability of different types of ACPs. Generally, the peak HRR for the ACPs increases when they are exposed to a larger heat flux. Among the 11 ACPs experimented, ACP03 and ACP07 possess with significantly higher peak HRR than others, which evidenced that applying these two ACPs as external walls in the building will greatly increase the associate fire risks. It is also observed that the peak HRR of ACP03 and ACP07 raises drastically under higher radiation heat flux. For ACP03, with the increment of heat flux from 60 kW/m^2, the peak HRR raised approximately 43% than the peak HRR recorded for 50 kW/m^2. Otherwise, the peak HRR only increased by 49% for ACP07 from 50 to 60 kW/m^2. Noteworthy, ACP03 and ACP07 are both composed of polyethylene cores. The product ACP01 has a better fire endurance since the lowest peak HRR and longest time to ignition were observed along with various heat flux. Oppositely, the ACP03 is determined as highly combustible. Therefore, it is essential to conduct further investigation on the combustibility and flammability of polyethylene-based ACP products. Awareness of the potential fire risks related to ACP products should be raised in the building industry, as the products contribute to rapid fire spreading along the building façade, the ACPs with polymer cores may also melt and drip to the ground, resulting in a secondary fire.

A large-scale facade test method is very complex, and there are many different factors that can affect its repeatability and reproducibility. When wood cribs or liquid pool fires are used, an uncontrolled variability is introduced.[139] The thickness of the test specimen will affect the exposure since energy will be absorbed by the boundaries before the fire reaches the facade surface, and the dynamical flow of hot gases may change and thus change the heat transfer to the facade. This is because the test system is built on the outside of the rig, making the distance from the fire source to the target surface longer for thick systems. Air movements around the test setup (the wind) may also have a significant impact on the test. Furthermore, the appropriate amount and nature of the fire source have been long debated and need reassessment. With the help of numerical modeling, it is possible to perform extensive parameter studies and thus determine which parameters, with a natural variation, have an important effect on the robustness of the test method. The use of simulations may also reduce the amount of large-scale development testing, which is inhibited by high costs.

5.2 | Simulation study on the cladding fire

Currently, large-scale fire testing remains the only possible route to gain knowledge about the flammability of exterior facades. However,

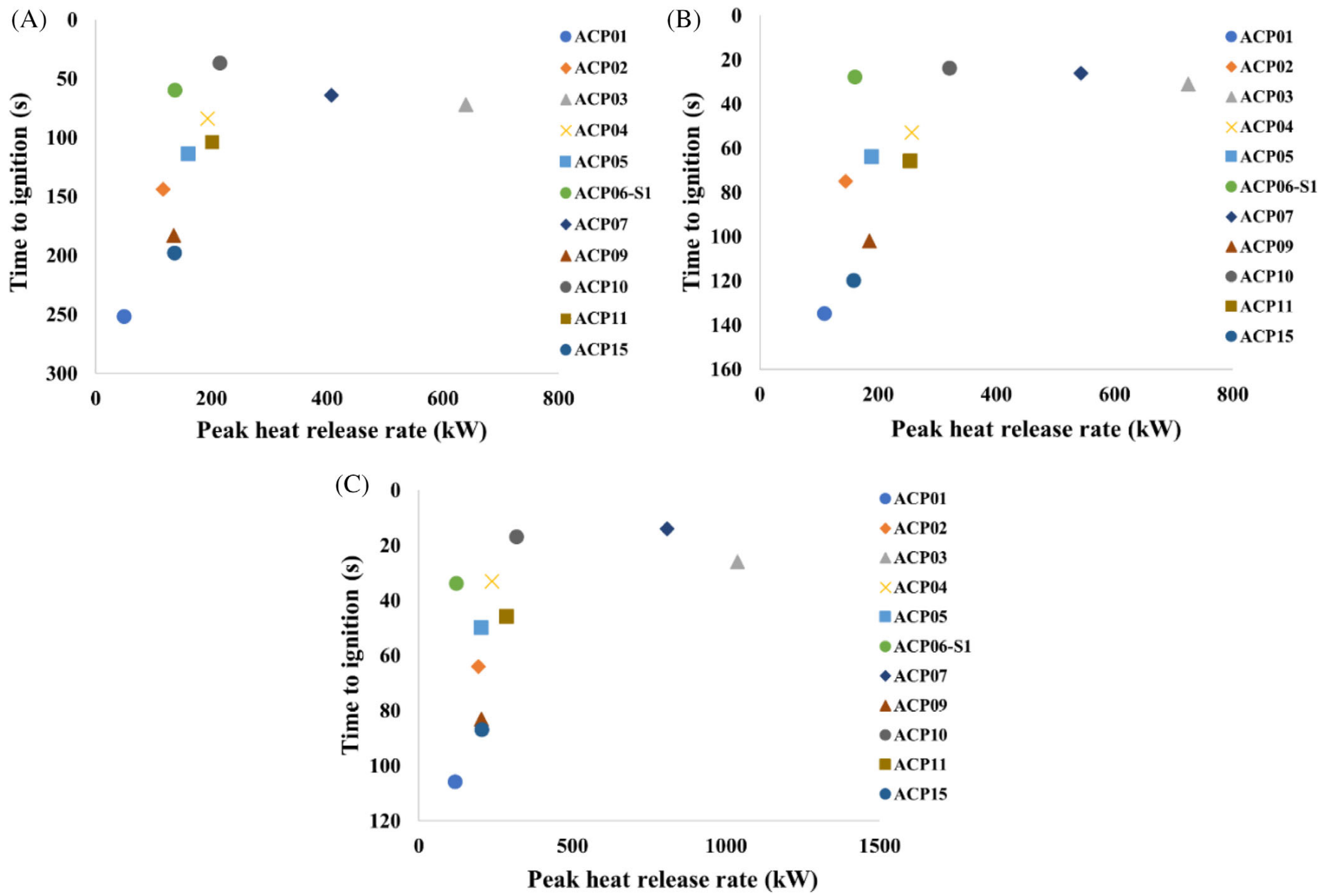


FIGURE 11 Time to ignition and peak heat release rate of ACP products (A) heat flux 35 kW/m^2, (B) heat flux 50 kW/m^2, and (C) heat flux 60 kW/m^2

these assessments are costly, destructive, and often impossible to conduct due to many practical constraints. Even when a large-scale test is performed, it is typically carried out on ideal constructed systems. In practice, the systems installed onto buildings may be vastly different from the testing standards. Furthermore, even flame-resistant polymers are still ignitable under immense radiation intensities. The key issues lie on how the polymer will perform in a realistic fire scenario and how much contribution they made to fire propagation. The application of computational fluid dynamic (CFD) modeling on building fires has become increasingly popular due to the rapid advancement of numerical methodologies and computational power. The heat and mass transfer, as well as the conservation of gas species and smoke particulates, can be aptly computed by CFD models with quality meshing and a good selection of numerical models. Therefore, numerical simulations based on CFD modeling are a cost-effective tool to bridge the knowledge gap and explore the system sensitivity to some of the parameters such as gap widths and material thicknesses. The developments of robust, effective numerical tool to address the needs of fire safety assessments of building materials will be beneficial to the building industry and government authorities, providing a complementary design tool for fire safety engineering design and fire investigation studies.

Currently, there have been several CFD fire field developed to simulate the burning of solid combustibles,[140] including the fire dynamics simulator (FDS) developed by NIST,[141] FireFOAM developed by FM Global, US,[142] and several others.[13,143] These models are developed under the large eddy simulation (LES) framework incorporating subgrid-scale (SGS) turbulence, combustion and soot generation, radiation, and pyrolysis models. Numerous computational studies at different scales and levels of fidelity have been conducted to predict the thermal degradation (pyrolysis) process of solid materials,[144,145] fire propagation,[146-148] suppression,[86] and other fire phenomena such as fire whirls[149,150] and soot formation.[151] Thermogravimetric analysis (TGA) and cone calorimetry have been the most commonly applied methods to characterize thermal degradation behaviors. The material thermal degradation curve obtained under dynamic or isothermal conditions presents different reaction zones mainly corresponding to the various component decomposition. Therefore, the majority of pyrolysis kinetic usually consists of multiple parallel reactions mechanisms and can be characterized by a summation of multiple Arrhenius expression:

$$r_{\mathrm{total}} = \sum_{i=1}^{N} r_i = \sum_{i=1}^{N} c_i A_i \exp\left(\frac{-E_i}{RT}\right)(Y)_i^{n_i} \qquad (1)$$

where k is the reaction constant, A_i and E_i are the pre-exponential factor and activation energy, respectively. R is the universal gas constant, T is the temperature of the solid, Y is the mass fraction of the solid, and c_i is the mass fraction for the individual component in the material. The subscript i denotes the number of components in the pyrolyzing material. All the constant parameters in the Arrhenius equation (ie, A_i, E_i, c_i, n_i) are commonly referred to as pyrolysis kinetics. Through the TGA data, there are numerous methods established to extract the pyrolysis kinetics (ie, activation energies and pre-exponential factor) of the underlying material.[152,153] Examples include the Kissinger,[154] Kissinger-Akahira-Sunose,[155] Flynn-Wall-Ozawa,[156] and the Friedman method.[157]

In terms of façade systems, there have been numerous computational studies on fire scenarios.[158-162] Some of them investigate elements of the façade such as air cavity[163,164] and material type,[165] while others focus on simulation of full-scale façade systems.[166,167] Due to the massive computation resources and high model complexity involved in full-scale façade simulations, most of the numerical studies focus on specific geometric elements. For instance, Kolbrecki[168] conducted a numerical investigation for estimating the movement of products of fire along facades. Chow et al[169] utilized FDS to investigate the fire and fire-induced aerodynamics behavior with a combination of different heat release rate (HRR) and air cavity depth. From the numerical simulations, more detailed smoke movement patterns can be observed, and the complexity of the potential danger related to different combinations of fire intensity and cavity depth was also revealed. Livkiss et al[164] conducted a numerical study of fire-driven flow in narrow cavities. FDS was used to simulate fire-driven flow between two parallel vertical walls. Flame heights, thermal impact to the interior wall surface, and upward flow velocities were predicted with FDS and compared with experimental results. Girado et al[170] performed numerical simulations of a three-storey ventilated façade fire scenario to investigate the effects of fire barriers, combustible and noncombustible thermal insulation, air cavity, and ventilation on fire propagation. FDS was applied for the fire simulations. The results highlighted the risks of ventilated cavity as a pathway for fire spread and emphasize the need for compartmentalization of cavities on each floor and noncombustible insulation material. Chen et al[171] conducted a series of simulation case studies on a two-storey cladding system with different initial fire sizes and air cavity widths in the cladding assembly. The results suggest that there is a trade-off regarding the air cavity width. A decrease in air cavity will result in a lower ignition criterion for the external cladding while increasing the cavity results in a more significant fire if the material is ignited. Simulation results illustrating the fire propagation through the cavities are shown in Figure 12.

Another key contributing factor to fire propagation in façade systems is the material type, and numerical studies offer a very cost-effective method to analyze the fire performance of different materials. Nguyen et al[165] conducted a comprehensive investigation on fire resistance of GFRP composite for building façade. A methodology incorporating both experimental (TGA, cone calorimetry, and single item burn test) and numerical simulation (FDS) was applied, and the conceptual diagram is shown in Figure 13. The experimental results were used as input parameters and validation to construct the numerical model. The model then provided more detailed insight into the burning process and flame spread behavior. Parametric studies are conducted to investigate the effect of fire-retardant additives on the fire performance of the composite sandwich panel. More recently, another fire modeling framework has been proposed to couple with pyrolysis data extracted from TGA and cone calorimeter to study thermal decomposition of flame-retardant polyurethane foams.[145] It was found that the heat release rate profiles were in good agreement with experimental data, and the total smoke release and total CO production also matched the experimental trends. The numerical studies focusing on materials highlighted above demonstrated that numerical models could be used as an effective assessment tool for analyzing the flammability and toxicity of building materials. Furthermore, these models could potentially be upscaled into larger simulations of full-scale realistic fire scenarios.

As mentioned previously, numerical studies of full-scale fire scenarios are limited due to the massive computation resources, high model complexity, and difficulty in model validation. These studies mainly focus on façade testing standards such as the BS8414-1. Hajduković et al[134] studied the fire performance of external thermal insulation composite system (ETICS) facades with expanded polystyrene. Two large-scale facades fire tests were performed with different incident heat flux upon the façade surface. The results were compared to numerical predictions from FDS. The authors concluded that the flame propagation across a thin-rendered EPS ETICS facade was not exclusively a problem of the applied materials but was closely connected to the facade shape. Bezas et al[172] investigated the sustainability of steel buildings in the case of a double-shell brickwork cladding, assessed under fire protection criteria and fire performance aspects. FDS was utilized to predict the temporal temperature distribution due to fire of a double-shell brickwork cladding, and the results were coupled to a Finite Element Analysis (FEA) model to investigate the effect of increasing temperature to the steel element. The results indicate that the steel-framed structures with double-shell brick cladding can be protected against fire effectively.

More recently, Dréan et al[173,174] conducted numerical studies on the fire behavior of facade equipped with aluminum composite material at both medium scale and large scale. The numerical model was constructed based on a series of façade fire tests performed according to the ISO 13785-1 and BS8414-1 standards. The model was used to investigate how each façade (ie, cladding material and insulant) component contribute to the overall flaming behavior. Aluminum panels with polyethylene and mineral core with poly-isocyanurate and dual-density wool insulations were tested. Figure 14 provides an illustration of the model geometry and simulation results. The authors concluded that aluminum cladding is the most important element driving global fire behavior of the facades and highly combustible core materials showed rapid fire propagation disregarding the insulant material used. Furthermore, the degradation of the cladding panel affects the integrity of the cavity.

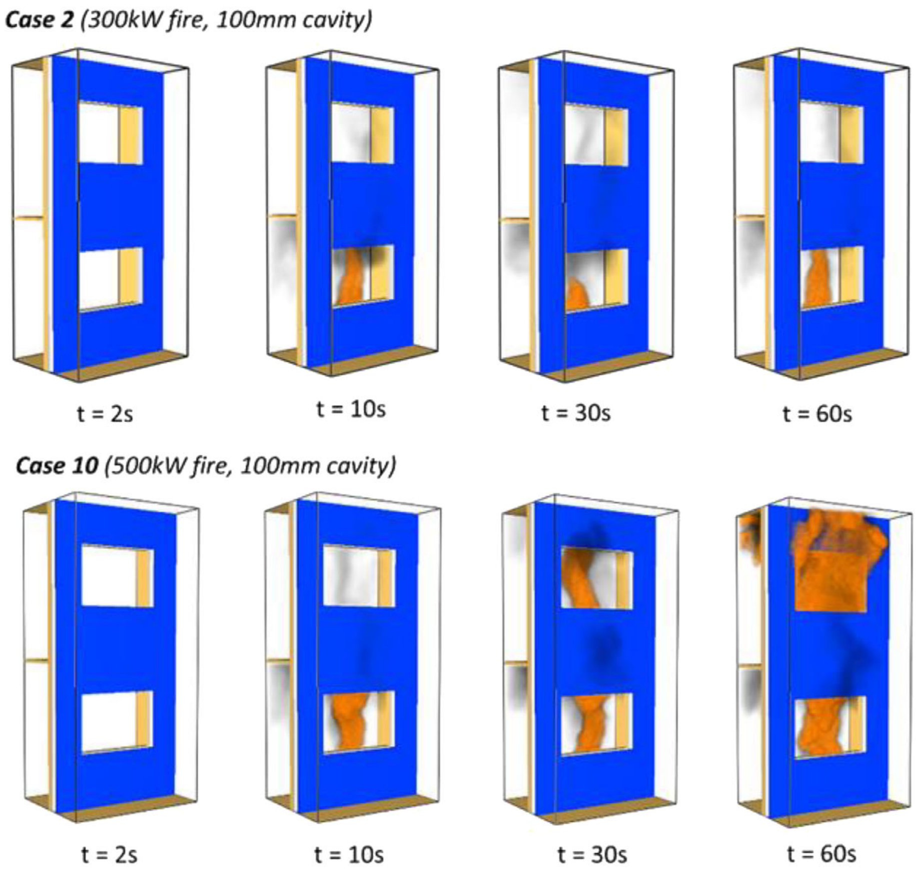


FIGURE 12 Graphics of fire spreading through the façade with different cavity width and fire size extracted from Chen et al[171]

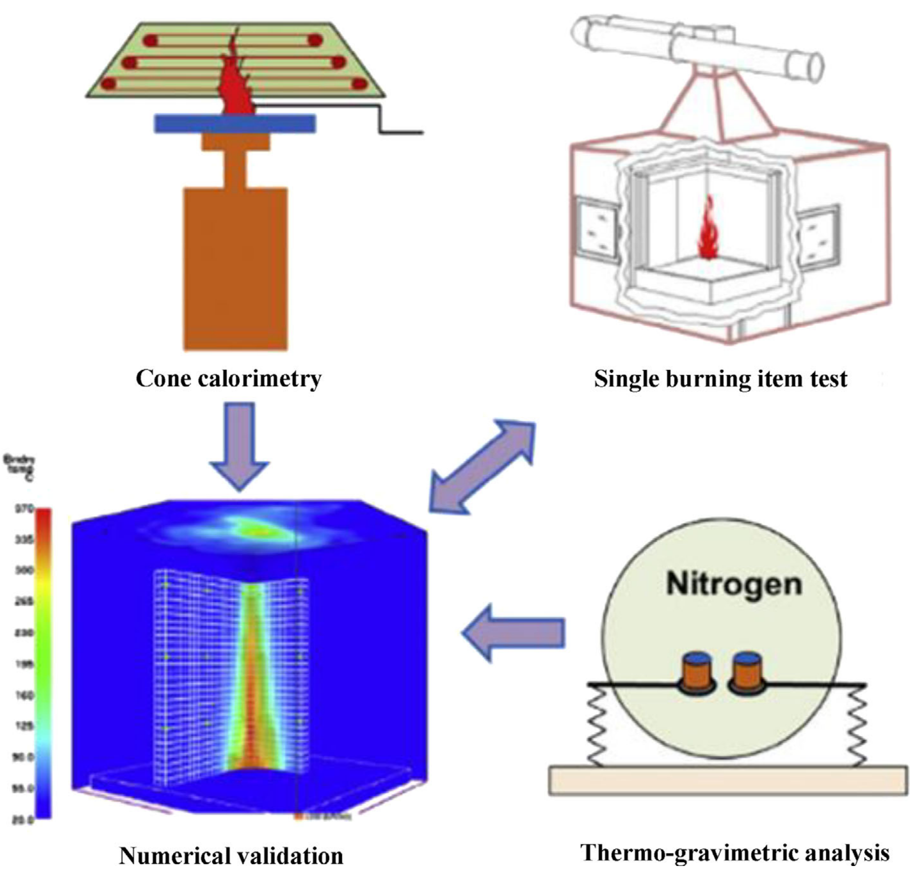


FIGURE 13 Methodology for combined experimental and numerical study for fire resistance of composite materials extracted from Nguyen et al[165]

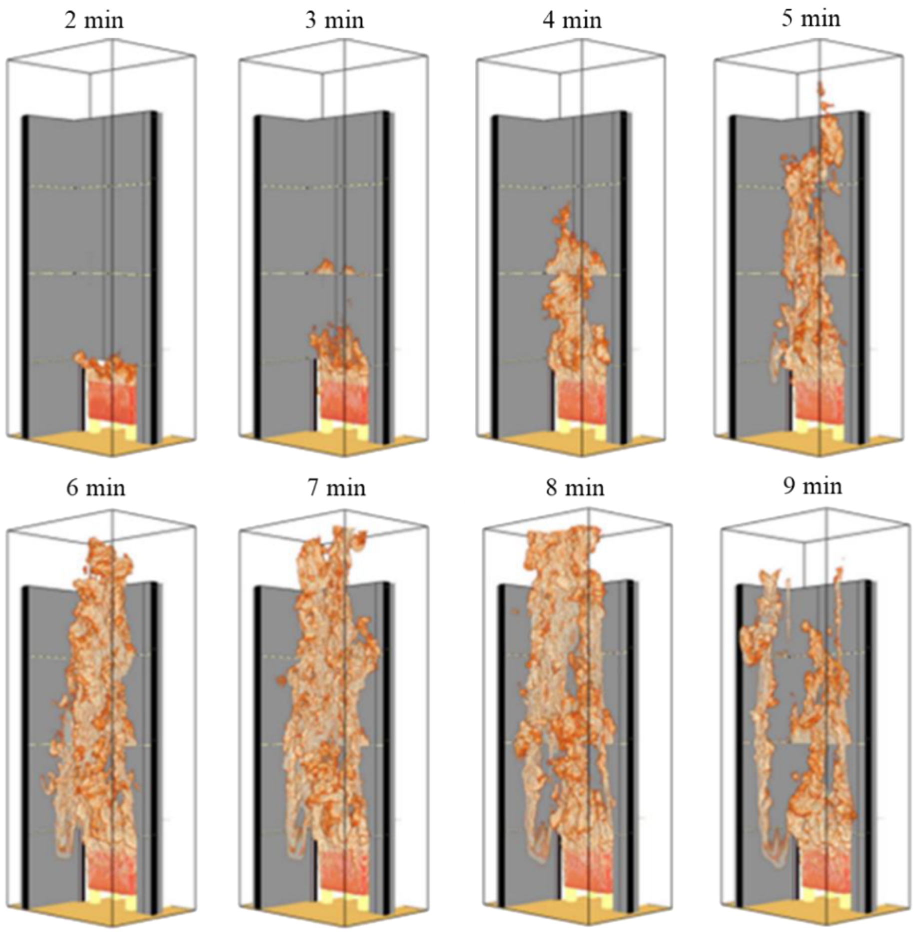


FIGURE 14 Graphics of fire spreading through the façade[173]

Guillaume et al has conducted a series of comprehensive case study on the Grenfell Tower fire incident in numerical modeling approaches.[175-178] In order to investigate the fire propagation and spread behavior, a large-scale CFD model of the Grenfell Tower has been constructed under the LES framework. The comprehensive numerical studies have replicated and analyzed the fire initiated from the compartment to the cladding system,[176] the vertical,[177] and horizontal fire propagation on the surface of the façade surface.[178] In Part I and II, Guillaume et al have established a compartmental fire simulating the fire spread from the initial flat to the exterior cladding system, including the vertical propagation and fire re-entry phenomenon; the model has been validated by the real fire observation in videos and pictures records shown in Figure 15. Further investigation on the impact of different building configurations including window shape, air cavity, and cavity barrier to the fire development and spread was addressed in Part III. Part IV demonstrates the fire behavior during lateral flame spread as well as the horizontal fire propagation rate at the crown level of the Tower is analyzed comprehensively. This series of studies not only elucidate the fire behavior of the external façade system but also can be further employed to study internal tenability conditions, for instance, toxic emission and thermal ambiance.

In short summary, the reviewed simulation case studies highlight the advantages of utilizing numerical models for fire investigation. It is a more cost-effective method to analyze the flame spread behavior of façade fires compared to experimental assessments, which are extremely expensive, destructive, and often impossible due to many practical constraints. As highlighted above, pyrolysis modeling based on CFD has developed into a viable tool for the assessment of potential fire hazard which would otherwise require large-scale fire tests. Furthermore, comprehensive parametric studies can be conducted to investigate the effects of specific parameters on the fundamental thermal degradation process, flame spread, and combustion that occurs in a fire scenario.

5.2.1 | Simulation limitations, verification, and validation

There are many assumptions and limitations in performing simulations of fire spread on facades as it is a very complex system. In terms of CFD methods, the combustion models mainly utilize a single-step reaction to evaluate the pyrolysis rate and determine the gas-phase fuel emission. The assumption of a single parent fuel places significant limitations on the prediction of pyrolysis yields in terms of accuracy and the range of species considered by the fire model. Furthermore, these methodologies lack an in-depth understanding of chemical mechanisms leading to thermal decomposition behaviors, in which the formation of char, chemical pathways of releasing of various gas

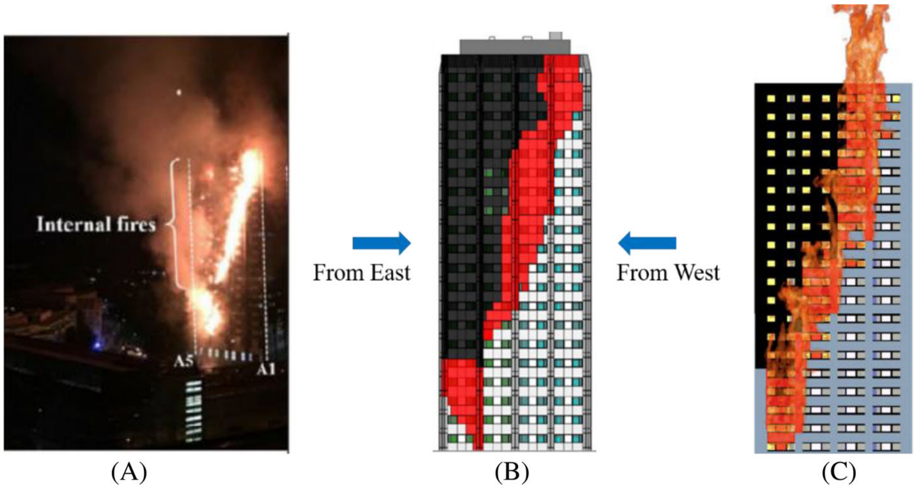


FIGURE 15 Comparison between real fire observations (A) and (B) and numerical simulation (C)[178]

volatiles, and melting of solid are not considered. Furthermore, some studies have highlighted the degradation of the cladding panel affects the integrity of the cavity.[173] The structural integrity is often not considered in CFD-based façade fire simulations. There are also the issues of melting and falling debris, two critical factors that contribute to façade fire spread.

Anderson et al[139] conducted a comparative simulation study on three large-scale facade testing methods, namely, the SP Fire 105, BS 8414-1, and the ISO 13785-2 methods. They evaluated the temperature and fire intensity sensitivity upon ±30% variations in five parameter variations. (ie, material thermal conductivity, density, specific heat capacity, heat release rate, and wind). They concluded with a list of recommendations for assessing uncertainties in the modeling of façade fires. It is recommended that apart from mesh sensitivity studies, researchers should also perform analysis on key model input parameters by testing the maximum deviation around a mean value. Furthermore, the combustible matter in façade is relatively small compared to the fire source. Thus, heat exposure on the façade should be measured. It is recommended to adopt a heat exposure curve or use controlled gas burners instead of a defined amount of free burning fuel.

Validation is another major challenge in conducting façade fire simulation studies. It requires quality and reliable data which are usually obtained through fire experiments, which are very limited. Therefore, there is a need for more experimental data on both laboratory scale (ie, testing the flammability of specific materials) and realistic fire scenarios. The most well-validated large-scale models are the SP Fire 105,[110] BS 8414-1,[107] and the ISO 13785-2.[108] The simulations are mainly validated by comparing against gas temperatures measured from thermocouple trees located at different locations along with the façade panel. Because the standard fire test all involves initial free burning fuel load (eg, wood cribs, liquid fuel pan), the initial fire is usually validated against an HRR profile.

For example, Dréan et al performed validation studies with both medium-scale ISO 13785-1 test[174] and large-scale BS8414-1 test.[173] The model was used to investigate how each façade (ie, cladding material and insulant) component contributes to the overall flaming behavior. The numerical results were compared against experimental results from thermocouples and the heat release rate of the fuel source. The vertical fire spread was also compared against visual observations. Overall, good agreement was achieved by the numerical models. The authors concluded that aluminum cladding is the most important element driving global fire behavior of the facades, and highly combustible core materials showed rapid fire propagation disregarding the insulant material used. Furthermore, the models can be extended to accommodate combustible materials in the facade system developed by evaluating additional tests and thorough characterization of materials.

Validations for actual fire events are even more difficult as there are no quality validation data from measurement devices. Nonetheless, of the limited simulation case studies of fire incidents, they are validated by visual observations of the fire spread. For example, the series of numerical investigations conducted by Guillaume et al on the Grenfell Tower fire.[175-178] The simulations were broken up into three parts, (a) single level of the apartment, (b) one entire exterior wall, and (c) the entire four exterior walls of the building. The thermomechanical analysis performed in Koohkan et al is used to validate the window failure criteria.[179]

5.2.2 | Future prospects in numerical modeling

Although CFD techniques are widely used to simulate the behavior of building fires, there are still many challenges that remain. For instance, validation is one of the major difficulties in conducting fire simulation studies. It requires quality and reliable data which are usually obtained through fire experiments. Additionally, there are very limited amounts of validation data available for full-scale façade test. Therefore, there is a need for more experimental data on both laboratory scale (ie, testing the flammability of specific materials) and realistic fire scenarios. It is also challenging to adequately characterize the complex chemical behavior that occurred during gas-phase combustion and the solid decomposition process. This includes both the conversion from the solid mass to gas products and the char formation. Most modeling developments are based on the improvement of the gas-phase models involving fluid interactions with the fire dynamics, turbulence, and radiation effects. Furthermore, they generally utilize a single-step reaction to evaluate the pyrolysis rate and determine the gas-phase fuel emission. The assumption of a single parent fuel places significant limitations on the prediction of pyrolysis yields in terms of accuracy and the range of species considered by the fire model. Furthermore, these methodologies lack an in-depth understanding of chemical mechanisms leading to thermal decomposition behaviors, in which the formation of char, chemical pathways of releasing of various gas volatiles and melting of solid are not considered. In addition, there are no existing methods to comprehensively characterize the toxicity releases in building materials. Essential chemical kinetic data for pyrolysis modeling are required for the assessment of their associated fire risks. Therefore, the fundamental knowledge linking up the solid decomposition and gas-phase models still needs to be thoroughly studied.

One potential methodology to bridge this missing knowledge gap in fundamental solid decomposition is via Molecular Dynamics (MD). MD simulation is a computational method based on statistical mechanics and thermodynamics theory to simulate the interactions and behaviors of various atoms and molecules. There is a wide range of community-driven MD software such as LAMMPS,[180] GROMACS[181] and CHARMM,[182] and commercial MD packages are also available. Atomistic-scale computational techniques provide a powerful means for exploring, developing, and optimizing promising properties of novel materials.

In MD, the molecular movement and interatomic interactions are governed by Newton's second law:

$$\sum F = \mathrm{ma} = m\frac{dv}{dt} = \mathrm{m}\frac{d^2x}{dt^2} \tag{2}$$

$$F = -\nabla E \tag{3}$$

where E the potential energy function. MD is based on the general relationship between bond distance, bond order, and the bond energy of interacting atoms. The energy function and the resulting interatomic interactions are driven by force fields and are an essential part of the computational simulation. There are different kinds of forcefields for various applications. Common force field includes COMPASS,[183] CVFF,[184] PCFF,[185] OPLS-AA,[186] ReaxFF,[187] and UFF.[188] Generally, MD can be applied to both the organic molecular system and inorganic molecular system.[189] MD simulations coupled with the Reactive Force Field (ReaxFF) can be used to gain a more in-depth knowledge of the pyrolysis breakdown of a material. ReaxFF is designed to allow the consideration of disassociation and the formation of chemical bonds. It provides insight into the mechanisms of the pyrolysis process because chemical reactions can be observed at the molecular level. ReaxFF MD has been utilized to successfully describe complex chemical reactions in a wide range of systems including thermal decompositions of polymers,[190-193] coal[194] and biomass[195] and has recently been adopted to study combustion and charring processes.[196,197] For instance, Liu et al[198] applied the ReaxFF MD to simulate the pyrolysis process of the high-density polyethylene (HDPE) system. Detailed reaction mechanisms were analyzed, and their work showed the potential of ReaxFF MD as an effective method for studying the detailed pyrolytic processes for polymers. Subsequently, Vaari et al[199] carried out MD simulations to study the effect of flame retardant (aluminum (tri) hydroxide (ATH)) on the thermal decomposition of polyethene. The results showed that ReaxFF MD was capable of describing the flame-retardant effects of ATH and a promising tool for investigating existing and emerging flame-retardant concept. Harpale et al[200] conducted MD simulations on the thermal ablation of highly cross-linked phenolic resin polymer. The model was able to not only characterize the pyrolysis process but also the surface regression rate and the char thickness of the phenolic resin as a function of temperature. An illustration of MD simulation of phenolic resin is illustrated in Figure 16.

In summary, MD removes the need for complex multiphase pyrolysis and charring models which require substantial prior knowledge on material characterization. MD simulations serve as effective computational experiments to characterize material properties and predict mechanical responses, which can potentially be applied to study façade materials such as ACP and other building polymers. Furthermore, the detailed decomposition process from solid to gas phases can be identified with the application of reactive MD simulation. This technique has great potential for CFD pyrolysis modeling applications by providing the essential precursors of combustible fuel gases in combustion models to significantly enhance the reliability of toxic gas, charring, and smoke particulate predictions.

All the aforementioned models (both CFD and MD) usually require extensive computational resources (ie, computational power and time). The time scale of the simulations can range from 0.1 to 0.001 second for typical CFD fire simulations to 1e-14 seconds for MD, while a full-scale fire test experiment can take more than 5 to 10 minutes. In addition, further data manipulations (ie, post processing) are usually required to determine tenability criteria (eg, the average height of the thermal interface, the maximum concentration of toxic gases, etc.) from the flow field information to indicate the safety level of the fire scenario and achieve optimal building designs solutions for fire safety.[201] To overcome these major challenges, one of the potential methods is the implementation of machine learning techniques, or more specifically, artificial neural networks (ANN). ANN or multilayer perceptron (MLP) is a type of model that uses a collection of interconnected nodes (perceptron) to represent the relationship between an input and an output. ANN has been widely used in recent years as a popular tool to model a wide range of engineering systems[202-204] because of their ability to learn and adapt to find complex relations between different properties. The application of ANN to fire research is still relatively new. However, pioneering studies[205-208] have highlighted the potential of applying ANN to fire problems. These include the modeling of fire detector responses, the actuation time of sprinklers, and the occurrence of flashovers. More recently, many fire studies based on ANN techniques have been applied with considerable success.[209-211] For instance, ANN models

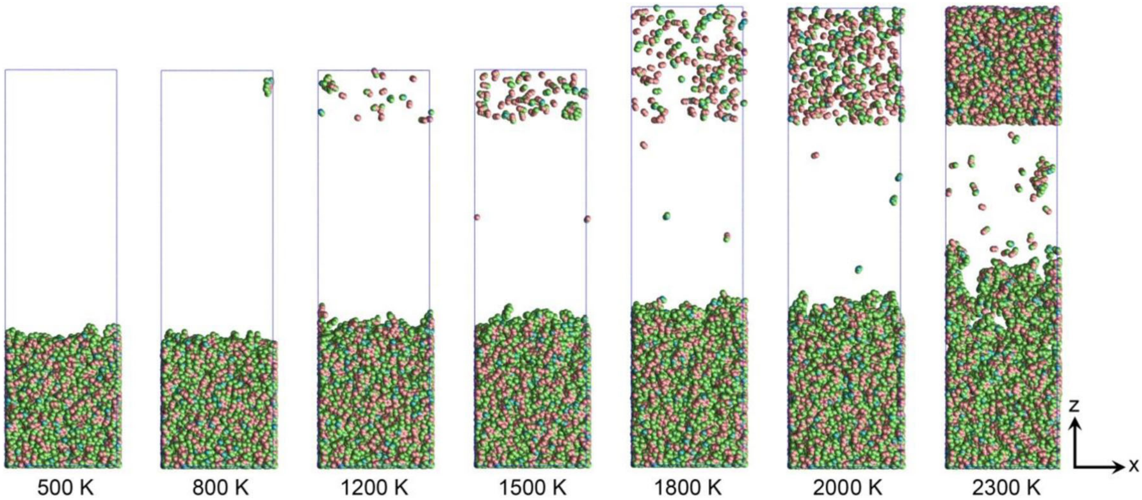


FIGURE 16 Illustration of reactive molecular dynamics (Reaxff) simulation of phenolic resin extracted from Harpale et al[200]

have become increasingly popular for analyzing spatial data related to forest fires,[212,213] driven by the significant advances of research in remote sensing and geographic information system. ANN-based model for estimating fire danger has also been proposed by Bisquert et al[214] and more recently by Satir et al[215] These models predict forest fire probabilities based on a wide range of climate and geological data such as vegetation type, temperature, elevation, and humidity.

Based on the literature review, there is an increasing trend for applying ANN for fire safety problems. Many of the techniques highlighted can potentially be applicable for predicting the fire dangers of façade systems. However, one of the challenges of ANN modeling is the quality and availability of training data. In this regard, there are research studies focused on improving the training datasets for the ANN model. For example, Lee et al[216] developed a novel ANN model for predicting parameters in compartment fires. The model has been developed by combining the general regression neural network (GRNN)[217] and Fuzzy ART (FA)[218] networks and was designed specifically for processing limited fire data. The results show that the ANN fire model can predict the location of the thermal interface with up to 94.5% accuracy and minimum computational times and resources.

In the future, a multiscale modeling framework incorporating aspects of the approaches above can potentially be developed into a highly robust and cost-effective design tool for fire safety engineering design and analysis of building façade materials in practical building fires and fire investigation studies. It will remove many practical constraints and significantly reduce the physical and environmental cost of physical experimentation.

6 | CONCLUSIONS

Rapid increases in fire incidents associated with combustible cladding materials especially ACPs have highlighted the importance of strengthening the measures in government policies, fire testing standards, and the replacement of combustible ACP products. Many of the severe cases have resulted in catastrophic damages in terms of human casualties, financial losses, and building damage. These catastrophic incidents have raised awareness and concerns by the public regarding noncompliant materials. It has been consistent rectification of the relevant building regulations in various jurisdiction worldwide. However, the issue of noncompliant materials in current existing buildings remains. Through our reviews, we achieved the following conclusions:

1. A collection of past fire incidents that were associated with façade fires from the previous three decades has been summarized. In overview, three major fire mechanisms have been identified in common in most of these fire incidents. Additionally, nine potential risks that could be resulted from the three additional fire spread mechanisms were identified based on past observation of fire scenarios through literature.
2. A detailed review of the building codes and fire testing methods has been completed. A brief summary of the Australian Taskforces, including the current research work, achievements and contributions, has been also delivered. A deeper understanding of the associated risks is not only beneficial to the building occupants, but also to frontline responders, who risk their lives during their response to fire events.
3. Both experimental and numerical studies on cladding systems have been reviewed in this paper to provide an in-depth understanding of the fire performance of various types of ACPs. Through the material database of ACPs market products conducted by the University of Queensland, it was found that the core material was the major contributing factor to the fire spread mechanisms of the external wall system.
4. The potential research forces applying machine learning algorithms–assisted computational simulations for fire predictions and molecular dynamics (MD) simulation have been highlighted. The future direction for fire safety engineering is proposed to gain a further understanding of the smoke/toxicity productions of the ACPs.

At the current stage, the fire testing protocol for cladding panels is still limited to the study of flammability and categorize different fire ratings for compliance. Nevertheless, the fire smoke and toxicity productions resulted from the burning of the polymers and/or flame-retardants are overlooked. While the inhalation of asphyxiated gases will remain one of the major factors for building fire casualties/fatalities, it is vital to enhance our building codes/standards for cladding panels to ensure the gas species generations are at an adequately harmless level. Furthermore, the smoke production rate should also be a measuring quantity within the fire testing standards. With the utilization of benchmark fire testing approaches including cone calorimetry, it is proposed to include new criteria for major gas species (ie, CO/CO_2) and soot volume fraction. To achieve this new protocol, it is also recommended to establish a systematic framework for researchers/building engineers to follow to establish a database related to ACP products. For instance, the solid decomposition kinetics can be characterized by thermogravimetry (TGA) test integrated with Fourier-transform infrared spectrometry for chemical species and smoke generation. Once the essential input data corresponding to the ACP products are developed, numerical fire predictive models can be utilized and validated by the Cone Calorimeter test, before further up-scale to full-scale realistic fire scenarios for further investigation of the potential fire spreading mechanisms. Finally, a standardized cladding fire simulation scenario incorporating the established ACP kinetics can be performed, and compliance criteria including temperature, CO, smoke height, radiation, and visibility are benchmarked against tenable conditions.

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