A. Khan, S. Lin, X. Huang, A. Usmani (2021) *Facade Fire Hazards of Bench-Scale Aluminum Composite Panel with Flame-Retardant Core*, **Fire Technology**, https://doi.org/10.1007/s10694-020-01089-4

Facade Fire Hazards of Bench-Scale Aluminum Composite Panel with Flame-Retardant Core

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Abstract

Facade fires in tall buildings are currently occurring more than once a month globally that are responsible for many casualties and billions of dollars in losses. In particular, the tragic Grenfell Tower fire in London caused more than 70 fatalities raised the profile of facade fire hazard. This work used well-controlled irradiation up to 60 kW/m^2 to re-assess the fire hazard of typical flame-retardant aluminum composite panels (ACPs). We found that the vertically oriented ACPs with the "non-combustible" (A2-grade) and "limited-combustible" (B-grade) cores could still be ignited above 35 kW/m^2 and 25 kW/m^2, after the front aluminum layer peeled off. The peak heat release rate of these ACPs could be higher than common materials like timber and PVC. Moreover, compared to the B-core panel, the A2-core panel showed a greater fire hazard in terms of a shorter ignition delay time, a higher possibility of the core peel-off, and a longer flaming duration. It is because the ACP is a complex system, and its fire hazard is not simply controlled by the core material. The structure failure of ACP in fire, including peel-off, bending, softening and cracking, could further increase the fire hazard. This research improves our understanding of the systematic fire behaviors of facade panels and helps rethink the fire risk and test methods of the building facade.

Keywords: Ignition limit; ACP panel; heat release rate; structure failure; peel off.

1. Introduction

Over the last few decades, the application of modern facade systems effectively improves the performances of high-rise buildings and provides multiple objectives of value to its occupants, and it is a cost-effective solution for thermal insulation, weatherproof (e.g., extensive rain) as well as the building aesthetics [1–3]. However, because of the existence of polyethylene (PE) and other flammable core materials in the facade [4–8], such systems have become a route for fire spread along with the building exterior and caused a number of recent severe fire accidents [2, 9–12]. Moreover, during facade fire, the toxic smoke which enters the building (through cavities, windows, or any other openings) can make occupants incapacitated and limit the egress time. For example, the recent tragic event of the Grenfell Tower fire in 2017 (Fig. 1a) had claimed 72 lives [13–15]. The facade system in the Grenfell Tower was mainly composed of flammable polyethylene and plastic foams [14, 15] (Fig. 1b), and further reports suggested that the smoke inhalation was the major cause of the deaths [16, 17]. Today, large fires associated with facade systems in tall buildings continue to occur at a rate of more than once a month globally and are responsible for many deaths and billions of dollars in losses [10].

There have been many standard facade fire tests (see Fig. 1c and Appendix) before the Grenfell Tower fire [18–21], but many of them are not specifically made for façade. Moreover, the testing criteria and sample sizes in these standard methods vary from country to country. For example, DIN 4102-1

[21] focuses more on smoldering combustion of the facade panel. The EN 13823 test [20], as part of the EN 13501-1 test, mainly concentrates on the smoke and dripping generation. Since the tragedy of the Grenfell Tower fire, façade fire has gained a global attention and attracted many studies on different aspects of façade fire hazard [22–30]. Bonner and Rein [10] explored many factors and objectives involved in a facade design that could enhance the intensity of the fire and compromise the performance of the facade system. Nam and Bill [26] developed a new intermediate-scale fire test (parallel panel test) to evaluate the flammability of wall and ceiling assemblies. White *et al.* [28] compared the various test methods and regulations for testing facade systems globally and recommended to better cover a multitude of facade material systems and a wide range of fire scenarios, such as large flash-over fires with excess pyrolysate burning outside the room of the original fire. Guillaume *et al.* [31–33] performed CFD analysis to understand the fire spread both vertically and laterally along with the Grenfell Tower, and a correlation between horizontal fire spread rate and the height of the building was created to explain the global behavior of facade fire. Chen *et al.* [34] numerically identified that the fire would spread from floor to floor before the designated egress time.

Fig. 1. (a) The London Grenfell Tower Fire in 2017 (Credit: Getty and Graham Peebles), (b) the composite cassette facade panel residue after the facade fire (Credit: Tudor Pop), and (3) examples of facade fire tests and standards (Credit: Niall Rowan, Andrew Walker, Tom Roche, NFPA, ASTM).

Polymer-based composite panels, such as the aluminum composite panel (ACP) used in the facade system, are well developed because of its lightweight, formability and cost-effectiveness [35–38]. Despite a high fire risk, old buildings and relatively newer buildings in some developing and developed countries still use the ACPs with flammable[1] core material [8, 39]. For example, the Grenfell Tower in London, TVCC Tower in Beijing, and Torch Tower in Dubai all used composite facade panels with flammable core components, which was the primary reason for the rapid vertical fire spread along the building facade [40].

[1] Flammable generally means that the material can support a flaming fire.

Based on the reaction-to-fire, the core materials of ACPs are classified into various grades, as described in EN-13501-1, DIN 4102-1 and other standards [21, 41]. According to EN-13501-1, the grade-A core material must pass non-combustibility test (*non-combustible* per DIN 4102-1). The grade-B core material is combustible but has more stringent requirement in terms of total heat release rate and fire growth (*limited combustible* per DIN 4102-1).[2] To reduce its combustibility, most of these core materials have a certain percentage of ceramics or other non-combustible materials (e.g., mineral matter), and the utilization of them is quite common in modern buildings in developed countries [42]. Table 1 illustrates the grading of different kinds of ACP's core materials utilized commercially. As the high-cost A1 core materials are rarely used, the "non-combustible" A2 core is a preferable choice for ACPs in terms of fire performance in high rise buildings. Besides, the B core materials are also widely used in ACPs and building facades, because they are considered as "limited combustible" [21, 41], although the concept of "noncombustible" itself is questionable [43]. Note that Table 1 is a short summary for reference only, and readers are encouraged to check the original description in the BS EN 13501-1, as well as other codes and testing methods. Various facade materials are summarized in Cladding Material Library of University of Queensland [4–8].

Table 1. Standard grading of the material reaction-to-fire performance based on BS EN 13501-1 [41].

Grade	Smoke Production Grade (Table A2)	Droplets Grade (Table A3)	Tests and reaction to fire performance	Remarks
A1	-	-	Pass non-combustibility test (ISO 1182, 1716) and single burning item test (EN 13823)	No flame, no smoke, and no flaming droplets/particles (non-combustible)
A2	s1/s2/s3	d0/d1/d2	ISO 1182, 1716, and EN 13823	smoke production and flaming droplets/particles; (A2-s1-d0) is regarded as "non-combustible" and widely used in high rise building exterior
B	s1/s2/s3	d0/d1/d2	Ignitability test (ISO 11925-2) and EN 13823	smoke production and flaming droplets/particles; B-s1-d0 is regarded as flame-retardant and "limited-combustible"
C	s1/s2/s3	d0/d1/d2	Ignitability test (ISO 11925-2) and EN 13823	smoke production and flaming droplets/particles, and support limited horizontal flame spread

Nevertheless, it is necessary to examine not only the core materials but also the whole ACPs as a unit for its proper performance. Unfortunately, in practice, the ACPs with the A2/B-grade core material is "automatically" considered as the "non-combustible" or "limited-combustible" panels. So far, the fire behavior of ACP (not just the core material) is limited. For example, McKenna *et al.* [17] tested ACPs with many core materials, such as the pure PE, as well as PE with fire-retardant materials and inorganic materials, at a heat flux of 50 kW/m^2 in cone calorimeter, compared the heat release rate, and measured the toxic emission gases. Few other studies have examined the overall fire hazard of ACPs as a system exposed to the well-controlled fire or fire irradiation.

In this work, bench-scale experiments are conducted to re-assess the fire hazard of ACPs with flame retardant A2- and B-grade core materials under well-controlled external irradiation from 20 to 60 kW/m^2. The ignition limit, ignition delay time, and heat release rate are quantified to enrich the existing database of cladding materials [4–7]. The fire and mechanical failure behaviors (e.g., peel-off, cracking, and bending) are discussed and analyzed in detail.

[2] The test standard does not explicitly define what are "non-combustible," "limited combustible," "flammable" etc., but these simple terminologies are widely interpreted and used in the market.

2. Experimental Methods

2.1. Setup and materials

Two types of ACPs with different core materials (grades of A2 and B via the BS EN 13501-1 test) were tested. All ACPs were customized into the same dimension of 10 cm × 10 cm × 0.5 cm for the standard cone calorimeter test [44], as illustrated in Fig. 2. Detailed chemical formula and composition are often commercial secrets and vary from manufacturer to manufacturer [4–7, 17]. For both types of ACPs, there is a 4-mm core material sandwiched between two 0.5-mm thick aluminum layers, which are combined by a thin layer of glue. The core materials of both ACPs have PE and fire-retardant additives to achieve desirable fire-retardant characteristics. The thermal analysis results of both core materials are shown in Fig. A1. The A2-grade core material has more inorganic additives, such as aluminum hydroxide ($Al(OH)_3$) and magnesium hydroxide ($Mg(OH)_2$), while the B-grade core material has a higher content of PE. The original masses of dried samples were measured as 76.3 ± 0.5 g for the panel with A2-grade core and 73.3 ± 0.5 g for the panel with B-grade core. As the mass of a single Al layer was 13 ± 0.2 g, the masses of A2 core and B core were 50.3 g and 47.3 g, respectively.

All experiments were conducted using the cone calorimeter (FTT iCone Plus) [44–46], and it mainly includes a conical heater, a spark igniter, and a sample holder, as illustrated in Fig. 2. Such a testing procedure was also used to evaluate the critical temperatures for insulation materials used in building assemblies [47]. The conical heater could provide a relatively constant and uniform infrared irradiation to the sample area of 10 cm × 10 cm. Before the test, the irradiation level of the conical heater was measured by a radiometer and calibrated with heater temperature. The test section, including the ACP sample, sample holder, and cone heater, was partially open to ensure a good air supply. The panel sample was vertically placed because most of the real building facade panels are vertical. Moreover, preliminary tests showed that if the ACP sample was horizontally placed with spark above the sample center, the ignition could not be achieved, because the Al layer stayed attached to the core and blocked the pyrolysis gas from reaching the spark.

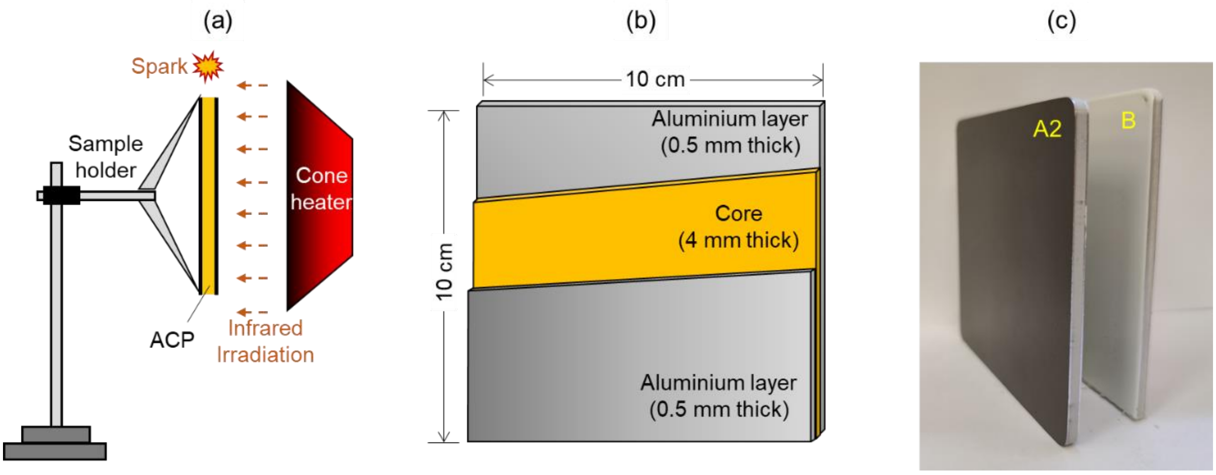

Fig. 2. Schematics of (a) experimental setup for bench-scale vertical aluminum composite panel (ACP) under external irradiation, and (b) tested ACP and photo.

2.2. Piloted ignition procedure

All ACP samples were first oven-dried for 24 h and then placed into an electronic dry cabinet to avoid the re-absorbing of moisture from the air. Before testing, the cone temperature was set at a certain value to generate the required irradiation from 20 to 60 kW/m^2 over the entire exposed face of the panel.

As illustrated in Fig. 2, the ACP sample was fixed by a sample holder to keep it vertical and parallel to the conical heater, similar to the method in [47]. The front painted side of the panel was exposed to the conical heater. The distance between the conical heater and the sample surface was calibrated before each test and remained constant at 25 mm. A spark acted as a pilot source was inserted and placed 5 mm above the centerline of ACP. The location of pilot source could affect the measurement of ignition delay time, so that its position was fixed in all tests to enable a fair comparison.

The radiant heating started once the shield of the conical heater was removed. Once the flaming ignition occurred, the spark was removed, while the heating was continued until the burning process ended. If the flame did not occur above the core material within 30 min, the ignition was considered as unsuccessful. Note that if this standard was applied to the horizontal ACPs sample, then no samples was ignitable. Afterward, the irradiation was adjusted to find the critical value for flaming ignition and other deformation phenomena. During the experiment, the complete processes from heating to the moment of flaming ignition followed by burning were captured by a side-view video camera. For each testing scenario, at least two repeating tests were conducted to reduce the random errors and ensure repeatability.

3. Results and Discussion

3.1. Ignition and burning phenomena

Once the panel was exposed to the irradiation, the paint of ACP burned very quickly for a few seconds before disappearing like a flash, as shown in Fig. 3(a). Such a flash burning is not considered as a successful ignition of the panel, although the brief flame more or less helped the heating process and may cause some hazards in large-scale facade systems. Figure 3(b-e) shows examples of typical heating, ignition and burning processes of ACPs with A2-grade and B-grade core materials under two irradiations of 25 kW/m^2 and 40 kW/m^2, respectively. Original test videos could be found in Supplemental Materials (Videos S1-4). As the heating continued, some smoke was always observed, which was likely the pyrolysis gases of flammable core components.

For ACPs with the A2-grade core material, under the lower irradiation of 25 kW/m^2, after heating for about 2 min, the aluminum layer facing the heating source first peeled off, as shown in Fig. 3(b). Then, the core material was directly exposed to the infrared irradiation. After heating for about 3 min, without ignition, the core peeled off as well mainly because of the thermal bowing (discussed more in Section 3.5). By increasing the irradiation to 40 kW/m^2 and heating for 1.5 min, the peel-off of the aluminum layer was also first achieved, whereas a flame could be piloted above the core surface immediately within a second, as shown in Fig. 3(c). Moreover, the glue attached to the Al layer was observed to get ignited, and the flame could still be sustained for several seconds after peeling off. The falling Al layer attached with flame was observed in the cassette facade system of the Grenfell Tower fire (Fig. 1a) and the ACPs from other facade fires, which may ignite the combustibles on lower floors. After the peel-off of Al layer, the core material burned for about 10 min with an intense flame.

For ACPs with B-grade core material, when exposed to the lower irradiation of 25 kW/m^2, the Al layer also peeled off first, as shown in Fig. 3(d). Afterward, the core became soft, mainly because its PE content is higher than the A2-grade core. Also, the surface glue and organic composition were slowly pyrolyzed and charred, so the residue surface turned into black without ignition. Unlike the panel with A2-grade core, the B-grade core material did not peel off from the back Al layer, regardless of the irradiation level and the existence of flame (discussed more in Section 3.5). On the other hand, under the higher irradiation of 40 kW/m^2, after radiant heating for 3 min, the peel-off of the Al layer was also first achieved. However, a flame could not be piloted immediately, different from the A2 grade core panel. Instead, additional heating (within 1 min) was needed for piloted ignition, as shown in Fig. 3(e).

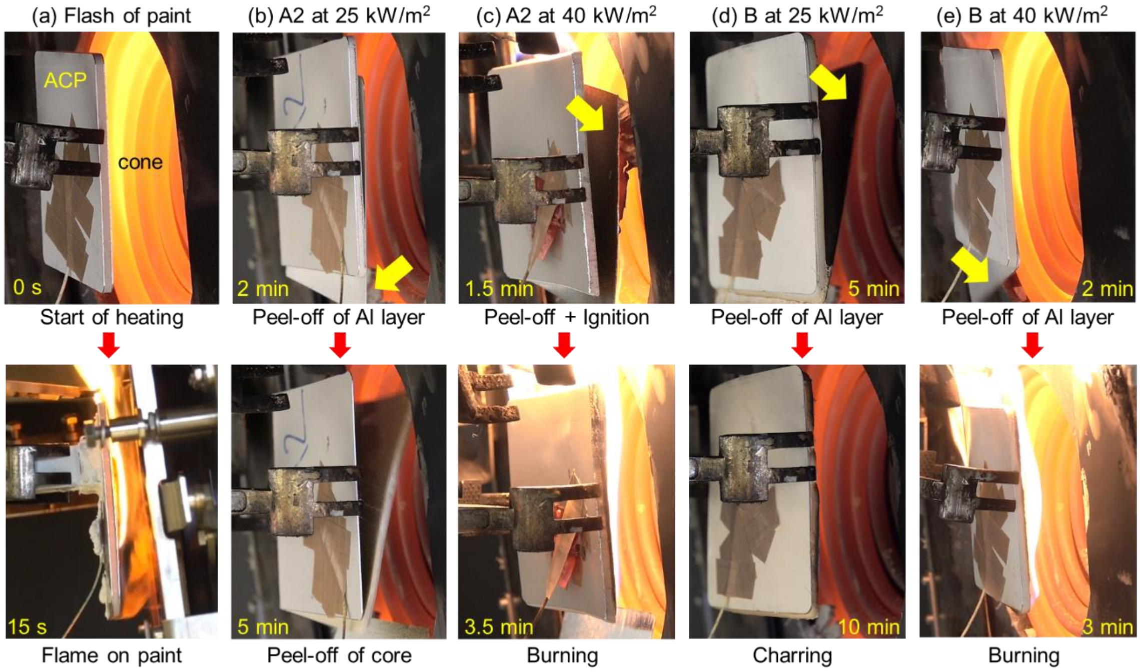

Fig. 3. Different burning phenomena of ACPs under various external irradiations, (a) flash of the panel paint, (b) panel with A2-grade core at 25 kW/m^2 (Video S1), (c) panel with A2-grade core at 40 kW/m^2 (Video S2), (c) panel with B-grade core at 25 kW/m^2 (Video S3), and (d) panel with B-grade core at 40 kW/m^2 (Video S4).

In short, both ACPs can support ignition and burning even at a relatively low irradiation level. In real fire scenarios, facades may receive a high heat flux from the nearby hot smoke plume and flames up to 100-200 kW/m^2. Therefore, it can be expected that ACPs with both A2- and B-grade cores can still sustain a flame for an extended period, even though they are considered as "*non-combustible*" or "*limited-combustible*", respectively.

3.2. Peel-off and ignition time

Figure 4 summarizes the peel-off time of front Al layer (t_{Al}: the time when the front layer of Al peeled off) and core materials (t_c: the time when the core was detached from the back layer), as well as, the ignition time (t_{ig}) of the core material for both ACP samples under different irradiations. As expected, both the peel-off time and ignition delay time decrease as the external irradiation increases. Compared to ignition, relatively lower irradiation is required for peel-off. For this experiment, the peel-off of the Al layer was a necessary condition for the piloted ignition. Although a small amount of visible smoke was also released before the peel-off of Al (see Videos S1-4), it was below the minimum fuel mass flux for piloted ignition [46]. Note that the location of pilot source could affect the ignition time, as observed in other pilot ignition tests [48, 49]. Nevertheless, as long as the pilot location was fixed and the same for both samples, a fair comparison could be made under this specific test condition.

For the panel with A2-grade core (Fig. 4a), when the irradiation level was below a minimum value of 23 kW/m^2, the Al layer would not peel off, and there was no visible change to the appearance of the panel. When the irradiation was lower than 35 kW/m^2 but larger than 23 kW/m^2, the exposed Al layer would first peel off, and after a while, the core would be detached from the back Al layer mainly due to thermal bowing and loss of adhesivity between core and back Al layer (discussed in detail in section

3.5). However, no ignition was achieved. The peel-off time of core was found to be almost twice that of the Al layer if it occurred (when irradiation was under 35 kW/m^2). For example, under the irradiation of 30 kW/m^2, the peel-off time of the Al layer and core were 113 ± 16 s and 220 ± 28 s, respectively. Moreover, as the external irradiation increased from 25 kW/m^2 to 60 kW/m^2, the peel-off time of the Al layer decreased significantly from 136 ± 20 s to 73 ± 13 s. When the irradiation was above 35 kW/m^2, the ACP core would no longer peel off ($t_c \rightarrow \infty$). Instead, a flame was piloted on the core right after the peel-off of the Al layer, so the peel-off curve merges with the ignition curve at high irradiation.

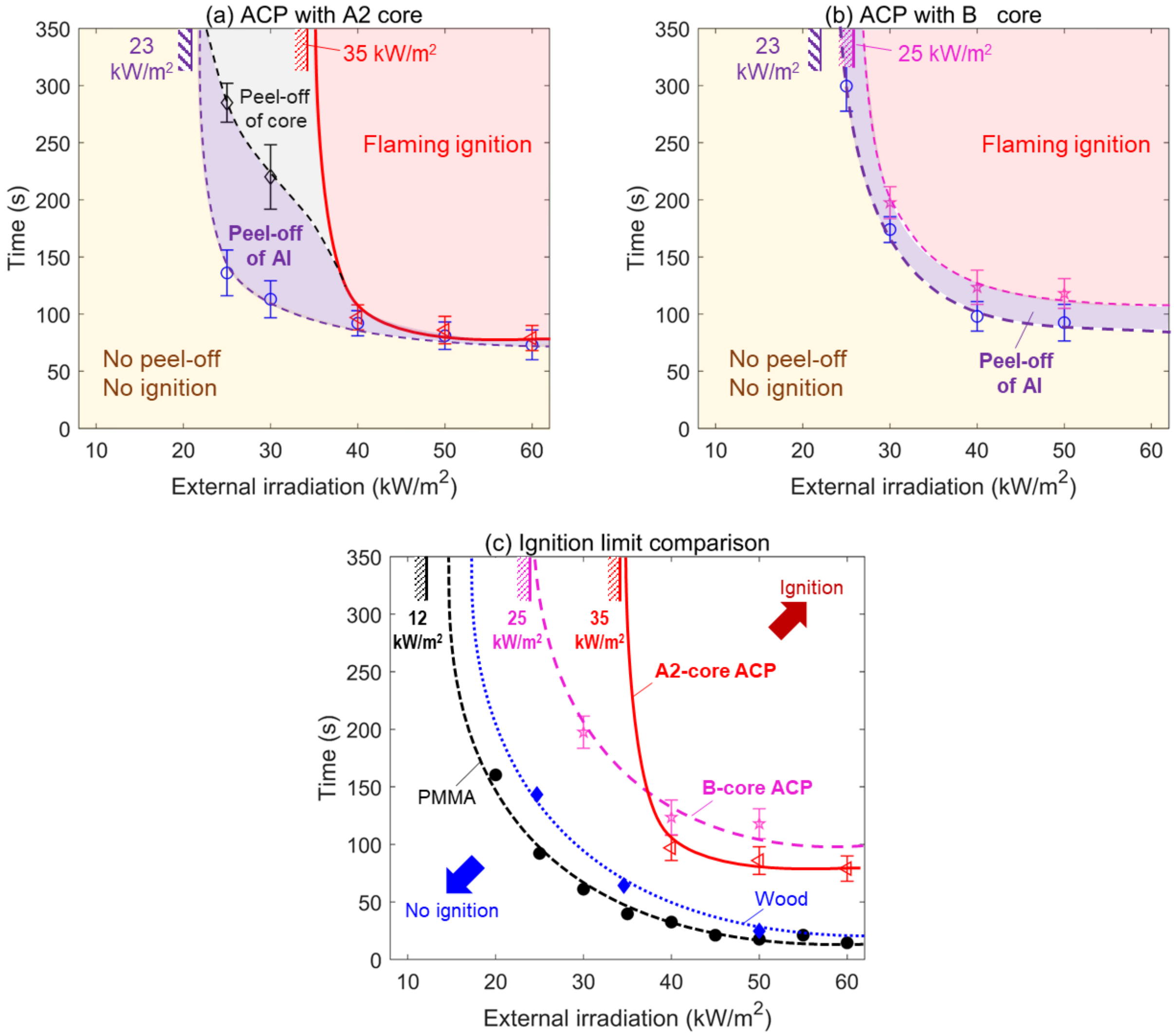

Fig. 4. Peel-off time and ignition delay time of ACP with (a) A2-grade core, (b) B-grade core, where the error bars show the standard deviations, and (c) comparison of ignition delay time and ignition limits of ACPs with data for PMMA [50] and dry wood [46, 51].

For the panel with B-grade core (Fig. 4b), the critical irradiation for the peel-off of the Al layer was also at 23 kW/m^2, the same as the panel with A2-grade core, because the same glue was used to stick core and Al layer. Then, ignition took place without the peel-off of the core material. For example, under the irradiation of 40 kW/m^2, the peel-off of the Al layer occurs at 98 ± 13 s, and it takes about another 25 s to achieve flaming ignition. Therefore, there was one curve for the peel-off of the Al layer and another curve for ignition that did not merge with each other.

3.3. Ignition limit of ACP

To evaluate the overall ignition characteristics of ACP panels, Fig. 4(c) compares the ignition-limit curves between the panels with A2- and B-grade cores, and the ignition-limit curves of PMMA [50] and dry wood (horizontal) samples [46, 51] from the literature are plotted as references. The intent for comparing with wood and PMMA is mainly to provide a better reference to ACPs, as these materials are widely used in the buildings. Although the minimum irradiation of ignition for the panel with B-grade core (25 kW/m^2) was smaller, the ignition delay time of it at heat flux above 35 kW/m^2 was longer than the panel with A2-grade core. In other words, as a typical vertical flame spread over the building facade has a heat flux above 50 kW/m^2 [52], the ignition and flame spread over the ACP with A2-grade core could be faster than the ACP with B-grade core. The observed faster ignition of A2-core panel is against the conventional ranking of *grades in the classification of the core material*. Thus, the fire hazard of the ACP facade panel as a complex system is not simply controlled by that of the core material.

Moreover, experiments further quantify the critical irradiation for the occurrence of peel-off and flaming fire, respectively. For both ACPs (with A2- and B-grade core materials), the critical irradiation for the peel-off of the Al layer is 23 kW/m^2, below which only thermal expansion could be observed. However, for panels with the A2-grade core material, the critical irradiation for flaming ignition is roughly 35 kW/m^2, while for panel with the B-grade core material, it decreases to about 25 kW/m^2. Therefore, from the viewpoint of minimum irradiation for ignition, the fire-resistance rating of ACPs with A2-grade core material may still be higher than that of ACPs having B-grade core.

The comparisons with PMMA and dry wood show that the minimum irradiation for igniting common flammable construction materials (about 11 kW/m^2) is much lower than those of ACPs [46, 50, 51]. In addition, the ignition delay time of tested ACPs is several-fold larger. Specifically, at 50 kW/m^2, the ignition delay times of ACPs with A2- and B- grade core materials are 81 s and 117 s, while for PMMA and dry wood, the ignition only takes 17 s and 24 s, respectively.

Note that the peel-off of the Al layer is a necessary condition, and for real large-scale ACPs in building facade, the Al layer may peel off faster due to a heavier Al layer, while the peel-off could also be partial and delayed due to the non-uniform heating. Thus, current curves may not be extended to larger scales, and the real flame heating from facade fire is not uniform and mainly convection from the flame. Therefore, it will be necessary to conduct the experiment under convection heating, and more large-scale experiments are required to further explore the burning behaviors and the corresponding ignition limit in various real fire scenarios.

3.4. Fire hazards

The major casualty in fire accidents is commonly caused by many reasons, such as the toxic products of combustion and the rapidity of ignition of building materials. In particular, the heat release rate (HRR) is an important parameter in characterizing the material fire risk and consequent fire hazards, such as the fire spread rate and structure failure [53]. Because the fire hazard increases with HRR, the peak HRR should be quantified for the facade panel. Based on the principle of oxygen calorimetry [46], the peak HRR per unit area ($\dot{Q}_p''$) can be approximated from the heat of oxidation

$$\dot{Q}_p'' = \frac{(0.21 - X_{O_2,min})V_a \rho_{O_2} \Delta H_{ox}}{A} \quad (1)$$

where V_a is the volumetric flow rate of air (m^3·s^{-1}), ρ_{O_2} is the density of oxygen (kg·m^{-3}) at the normal temperature and pressure; X_{O_2} is the minimum mole fraction of oxygen in the 'scrubbed' gases (removing water vapor and acid gases) during flaming combustion; $\Delta H_{ox} \approx 13.1$ MJ/kg is the heat of oxygen for most hydrocarbon fuels [54]; and A is the cross-section area of the sample, respectively.

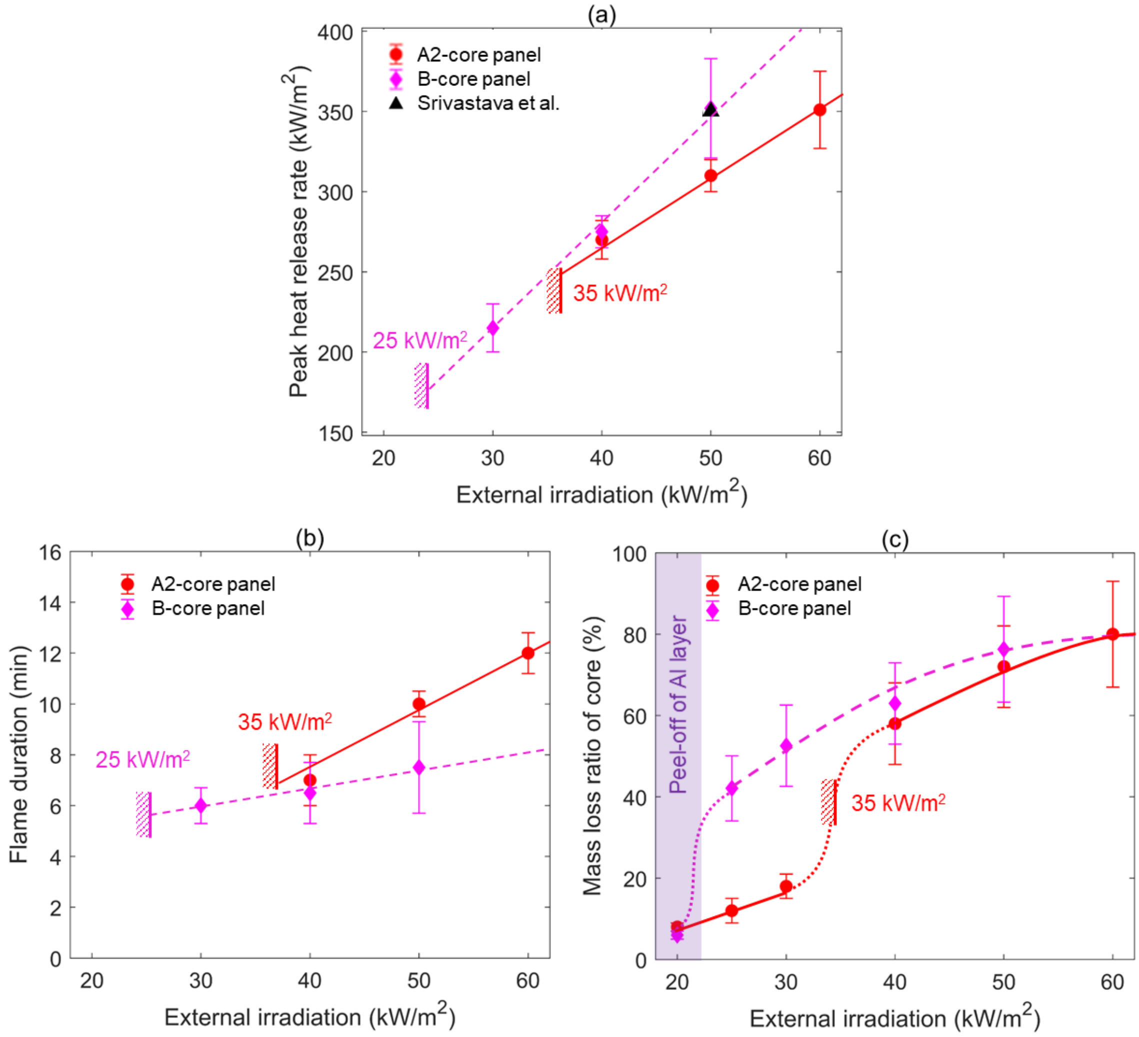

Fig. 5. (a) The peak HRR of ACPs with A2- and B-grade core with data from [2] under irradiation of 50 kW/m^2 for comparison, (b) flame duration of ACPs with A2- and B-core, and (c) Mass loss ratio of core materials under different irradiations, where error bars show the standard deviations.

Figure 5(a) summarizes the peak HRR of both ACPs above their minimum ignition irradiations, and compared with one test data from [2]. The example raw data of HRR curves vs. time are presented in Fig. A2. As expected, the peak heat release rate increases almost linearly as the external irradiation increases, following the same trends of other combustibles [55, 56]. For example, for the ACP with B-grade core, as the external irradiation increases from 30 kW/m^2 to 50 kW/m^2, the peak HRR increases from about 200 kW/m^2 to 350 kW/m^2, which is also comparable to the value from [2].

Under the same external irradiation, the peak HRR of the ACP with A2-grade core is found to be lower than that of the ACP with B-grade core. Thus, from the viewpoint of HRR, the fire hazard of ACP follows the ranking of the core material. More importantly, the peak HRR is also found to be higher than other common flammable materials. For example, under the irradiation of 50 kW/m^2, the peak value of A2-grade core material (~300 kW/m^2) is higher than ~250 kW/m^2 of dry timber [57], 96 kW/m^2 of Nylon/glass fiber, 286 kW/m^2 of wool, and ~150 kW/m^2 of PVC, although it is lower than ~750 kW/m^{2}of PMMA and ~1500 kW/m^2 of pure PE [46]. Therefore, the fire hazard of the so-called "non-combustible" and "limited combustible" ACPs will still be a primary concern due to its fast-developed market.

Figure 5(b) compares the flaming duration of the panels with A2- and B-grade cores under different external irradiations. Following the same trend of peak HRR, the flame duration also increases linearly with the external irradiation. For example, for the panel with B-grade core, the flame duration increases from 5.9 min to 6.5 min as the external irradiation increases from 30 kW/m^2 to 50 kW/m^2. Although the peak HRR of ACPs with A2-grade core is lower than that with B-grade core, the flaming duration of A2-core panel is found to be larger than that of B-core panel. Note that in real facade fire scenarios, the difference in ignition time becomes less importance under the heat flux above 100 kW/m2, but the burning duration will be of higher relevance. Thus, a longer burning duration of A2-core panel showing a more significant fire hazard.

Figure 5(c) compares the mass loss ratios of core materials for both APCs. Below 23 kW/m^2, no peel-off phenomenon was observed, and only a small amount of smoke was released, causing a small mass loss ratio (~5%). Above the ignition limit of 25 kW/m^2, the mass-loss ratio of B-grade core continuously increases with the external irradiation until reaching a plateau of about 80%, where only inorganic components remain in the residue.

For the A2-core panel, when the external irradiation was between 23 and 35 kW/m^2, the Al layer would first peel off, and then, the core would only be directly heated by irradiation for a short period until the occurrence of peel-off from the core. Therefore, there is an increase in the core mass loss with the level of irradiation, but without flaming ignition, the overall mass loss is lower than 20%. When the irradiation was above the ignition limit of 35 kW/m^2, the ACP core would no longer peel off, and a flame was piloted on the core to burn for several minutes, which resulted in a larger mass loss. As the external irradiation increased from 40 kW/m^2 to 60 kW/m^2, the mass loss ratio of A2-grade core increases significantly from 58 ± 10% to 80 ± 13%. Note the mass loss also include the water vapor from the decomposition of $Al(OH)_3$ and $Mg(OH)_2$ into Al_2O_3 and MgO (see more discussion in Section 3.5), so the mass loss ratio could be higher than its organic content. In general, under the same irradiation level, the mass loss ratio of B-grade core is found to be slightly higher than that of A2 grade core, thus, showing a higher fire risk.

Table 2. Summary of fire hazards for A2 and B grade core ACPs from different aspects, where the ACP parameter with a larger fire hazard is marked.

Parameter	A2 grade core ACP	B grade core ACP
Min. irradiation for ignition		smaller
Ignition delay time	shorter	
Peel-off of core (Y/N)	Y	N
Peak HRR		larger
Flaming duration	longer	
Core mass loss		larger

Table 2 summarizes the fire hazards of both ACPs from different aspects. Compared to the ACP with "limited-combustible" B-grade core, the ACP with "non-combustible" A2-grade core shows a more significant fire hazard in terms of a shorter ignition delay time, possibility of core peel-off, and a longer flaming duration, which is contrary to the traditional grade of ACP. Although more tests of larger ACPs are needed to make a thorough comparison, the current study can at least conclude that the traditional classification of panel fire hazards simply based on the combustibility or reaction-to-fire of the core material is insufficient to evaluate the overall fire performance of ACPs in real facade fires.

3.5. Structural behaviors

During the lab experiment, complex structural behaviors of ACPs could be observed once it was exposed to the external irradiation even to low irradiation. Thus, it is vital to describe and understand the structural responses of ACPs to assess the overall facade-fire hazards in real fire scenarios.

Peel-off. Aluminum layers are usually bonded with the core material by the polymer-based adhesive [58]. The characteristics of the adhesive (i.e., glue) are vital for the performance of ACPs [59], as it has been reported that approximately 70% of the failure of structures is initiated from the joints [60]. Once heated in a fire, the adhesive and tensile strength of polymer-based glue are significantly reduced and may finally cause the structure failure by removing the bond between metal layers and core [61, 62]. During the experiment, it was measured that the glue between the front Al layer and the core started to lose its adhesive strength and peeled off when the outer surface of the Al layer reached about 400 °C.

On the other hand, the peel-off of the core material from the back Al layer is more complex. For the B-grade core, it has a larger fraction of PE (see Fig. A1a), and the molten PE sticks to the back Al layer to prevent the peel-off of the core residue. For the A2-grade core, the fraction of PE is too small to stick to the back Al layer, especially when the panel is slowly heated (23-35 kW/m^2) above the melting point of PE. As a result, the core gradually peels off driven by its own weight (Video S1). However, if the irradiation exceeds the ignition limit (> 35 kW/m^2 and see Video S2), the intense heating from flame plus external irradiation may decompose $Al(OH)_3$ and $Mg(OH)_2$ into Al_2O_3, and MgO [63, 64] as well as oxidize the back Al layer into Al_2O_3. Then, the Al_2O_3 in both the core and back layer creates a strong bond to prevent the peel off. Further experiments are needed to quantify the bonding between core and Al layers under different heating conditions.

Softening and charring. For the A2-core panel, a clear pyrolysis process with visible smoke occurred, even below the minimum irradiation for ignition (35 kW/m^2), where the sample surface started to turn into char before peel-off, as shown in Fig. 6(a). However, ignition was not achieved due to the lower mass flux and flammability of the pyrolysis gases as flammability of the charring polymer is usually much lower than the non-charring one [65]. On the other hand, for the B grade core panel, it first started to soften and deformed with the Al layer before a clear pyrolysis or charring process. This is mainly because the B grade core has a relatively larger amount of PE component that has a low melting point of about 130 °C [66]. Nevertheless, the PE component of both ACP cores was not sufficient enough to form the dangerous dripping phenomenon [29, 30], which was observed in facade fires with panels of a high PE composition [17].

Thermal cracking. The thermal cracking of core was found in the residues after ignition and burning as well as under high irradiation without ignition, as shown in Fig. 6(b). A similar cracking phenomenon has been widely observed for timber materials [67, 68]. Under the external irradiation, the front surface of the core was first heated, which created an enormous internal thermal gradient because of a smaller thickness (i.e., 4-mm). Due to higher temperatures at the front surface, the topmost layer started to expand, while the subsequent layers remained at lower temperatures and restrained the expansion of the front surface. It eventually creates tensile stresses within the panel, and as a result, these restraints stresses created cracks. This behavior is highly critical, because cracks will (1) increase the surface-to-volume ratio to heat unexposed layer quicker, (2) help release the pyrolysis gas in-depth, and (3) reduce the overall structure stability of ACP. As a result, cracking can increase the HRR and facilitate the vertical fire spread. More large-scale experiments are required to further explore the fire hazards associated with the cracking phenomena.

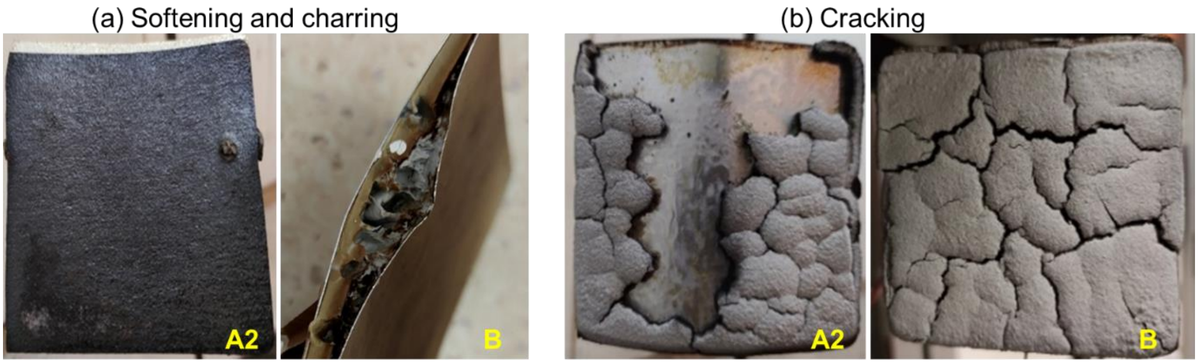

Fig. 6. (a) Softening of ACP with B-grade core and charring behavior of ACP with A2-grade core at low irradiation of 20 kW/m^2 (no ignition), and (b) thermal cracking pattern of residue after burning for ACPs with B- and A2-grade core at high irradiation of 40 kW/m^2.

Thermal bowing and bending. Similar to the thermal cracking discussed above, the large thermal gradient within the ACP can lead to thermal bowing and bending. As the only front face was heated and the unexposed surface remained at a lower temperature, thermal bowing occurred due to differential thermal expansions at different sides. In this experiment, the front of ACP was unrestrained like the real facade panel, and an unrestrained member of certain thickness would bow in a circular arc whenever experience a thermal gradient across its thickness [69, 70], as shown in Fig. 7. Note that a higher degree of bowing was observed at lower irradiation. As at lower irradiation, it took a comparatively long time for the front layer to separate; as a result, the panel had more time to get heated and expand, and eventually bow towards the heating side.

Under low irradiation, although ignition and flame do not occur, the thermal bowing would affect the fire performance of facade panels. Specifically, the core material can completely fail and peel off, exposing the internal building structures to facade fire. For the A2 grade core (Fig. 7a), the core showed a clear thermal bowing before peeling off from the back Al layer. For the B grade core (Fig. 7b), it was first softened but kept sticking with the back Al layer. In this sense, B grade core panels, by holding the core residue, show a better fire performance in protecting the building structure.

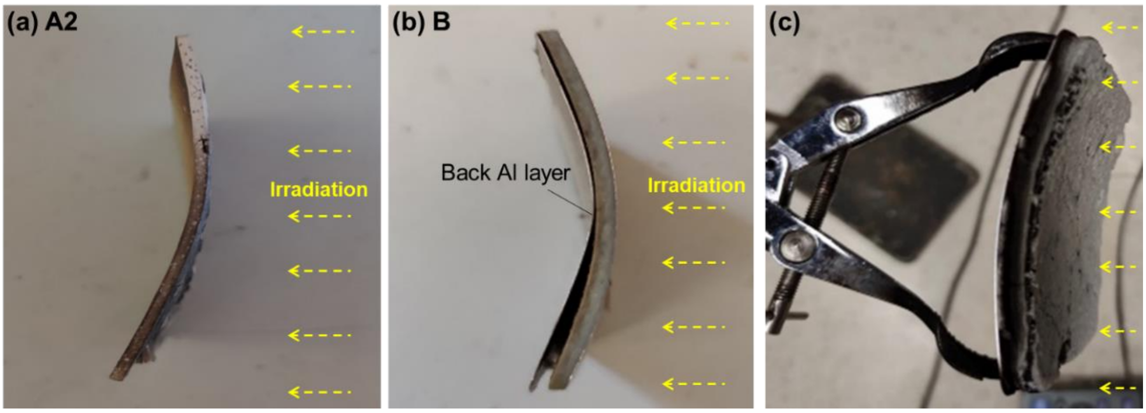

Fig. 7. Deformation behavior of ACPs exposed to external irradiation: (a) the bowing of the A2 grade core ACP and (b) B grade core ACP, and (c) the bending of ACP.

When ACPs are exposed to larger irradiation, the front layer usually peeled off, and the bending was observed after the peel-off of the front aluminum layer, as shown in Fig. 7(c). There are two possible reasons. Firstly, the unexposed surface was restrained by the sample holder, which created stress to bend towards the softer side. Secondly, the pyrolysis of the front core material also reduced the stiffness on the front [70]. In terms of the bending of the unexposed layer at higher heat fluxes, both types of panels behave similarly. Note that whether bowing or bending would occur in real facade fire depends on the different thermal expansions of the core material and aluminum, the scale of panel and fire, and the heat flux distribution of facade flame.

4. Conclusions

In this work, we re-assessed the fire hazard of typical "flame-retardant" facade aluminum composite panels (ACPs) under the well-controlled external irradiation. Results showed that ACP with "non-combustible" (A2-grade) and "limited-combustible" (B-grade) core materials could still be ignited and burning for an extended period above 35 kW/m^2 and 25 kW/m^2, after the peel-off of the front aluminum layer. Moreover, compared with many common flammable materials (e.g., dry timber, wool, and PVC), the peak HRRs of both ACPs are much larger. Therefore, the fire hazard of the "flame-retardant" ACPs will still be a major global fire safety concern.

Moreover, compared to the ACP with B-grade core, ACP with A2-grade core could show a more significant fire hazard in several aspects, (1) a 20% shorter ignition delay time above 40 kW/m^2, (2) a higher possibility of core peel-off at 25-35 kW/m^2, and (3) a 10-40% longer flaming duration, although the A2-grade core is more flame-retardant. Because the ACP is a complex system, its fire hazard is not simply controlled by the core material but also by the failure of structure and system.

Under lower irradiation, even without ignition, the long-term heating could still cause serious deformation of the ACP panel. The severe structural failure, including the peel-off of Al layer and core, bending, softening, and cracking, not only reduced the stability of façade system but also increased its fire hazard. In future work, more research, including experiments of different scales and numerical simulations coupling CFD and FEA, are needed to further explore the deformation of facade panels. This research improves our understanding of the systematic fire behaviors of facade panels and helps rethink the fire risk and test methods of the building facade.

Acknowledgments

This research is funded by the National Natural Science Foundation of China (No. 51876183), Hong Kong Polytechnic University Emerging Frontier Area (EFA) Scheme of RISUD (P0013879). Authors thank for Prof. Jose Torero (University College London) for inspiring this research.

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Appendix

There are various standard methods to test cladding materials or metal composite panels are used, e.g. ASTM E-84 in USA with the guidelines of test methods in NFPA 285 and BS 8414-1 in the UK, as listed in Table A1.

Table A1. Typical testing standards and methods for cladding materials or metal composite facade panels.

Standard abbreviation	Content
ASTM E-84	Measures the distance of the flame spread and the light obstruction of the smoke development
BS 476- Part 6 and 7	Measures speed and distance of flame spread
BS 8414-1	Assess the behavior of a non-loading bearing exterior cladding, it also measures mechanical performance as well
NFPA 285	Evaluate the inclusion of combustible material within wall assemblies. The fire performance of the entire exterior wall
EN 13823	Spread of flame and generation of smoke and also burning droplets
UL 723	Uses the test methods of ASTM and NFPA 285
ANSI/FM 4880	Tests the combustibility ratings of building panel assemblies with specific height installation
ISO EN 1182	Determine the non-combustibility performance of materials
ISO EN 1716	Determine the gross heat of combustion of the materials
ISO EN 11925-2	Determine the ignitability of the building materials
DIN 4102-16	Fire resistance test for building material

Tables A2-A4 list the details of the classification for material in EN 13501-1. Note that these tables only show the grading of materials widely found in marketing literature based on their combustibility and flammability. It is not the authors' intention to praise or critize any standard test. The authors encourage the readers to refer to the relevant standard and testing methods and check for more details in the references.

Table A2 Smoke production classification in EN 13501-1

Smoke classification	**s1**	**s2**	**s3**
Smoke production rate (m^2/s^2)	≤30	≤180	not s1 or s2
Total smoke production in 10 mins (m^2)	≤50	≤200	not s1 or s2
Definition	No or little smoke	A lot of smoke	substantial smoke

Table A3 Classification for flaming droplet/particles in EN 13501-1

Droplet classification	**d0**	**d1**	**d2**
Droplet production	No flaming droplet in 10 min	No droplet persisting more than 10 sec in 10 min	not d0 or d1

Table A4 Classification for material

Classification of material						Reaction to fire	Remarks
DIN 4102-1 [21]		**EN 13501-1** [41]					
Grade	Testing	Grade	Smoke Production Grade (Table A2)	Droplets Grade (Table A3)	Testing		
A1	DIN-4102-1	A1	-	-	EN ISO 1182, 1716, EN 13823	Non-combustible	Supports no flame
A2	DIN-4102-16	A2	s1	d0	EN ISO 1716, EN 13823		Highly preferable in high rise building exterior
B	DIN-4102-16	B	s1	d0	EN ISO 11925-2, EN 13823	Combustible, but limited flammable	Low flammability, regarded as fire retardant composite panel, difficult to spread quickly
B	DIN-4102-16	(A2, B), C	(s1/s2), s1/s2/s3	(/d1/d2), d0/d1/d2	EN ISO 1716, 11925-2 EN 13823	Combustible (except A2) with higher smoke and droplets production	
B2	DIN-4102-16	D, E	s1/s2/s3	d0/d1/d2	EN 13823, EN ISO 11925-2	Flammable	Restricted to use as signage only
B3	DIN-4102-16	F	-	-	No test (Failure of E)	Easily flammable	

The thermal analysis of A2 and B core materials was conducted under argon gas flow at two heating rates of 10 and 20 K/min, respectively. The initial mass for testing was about 10 mg. Fig. A1 shows the normalized mass loss and mass-loss rate (%/min) of A2 core and B core varying with temperature.

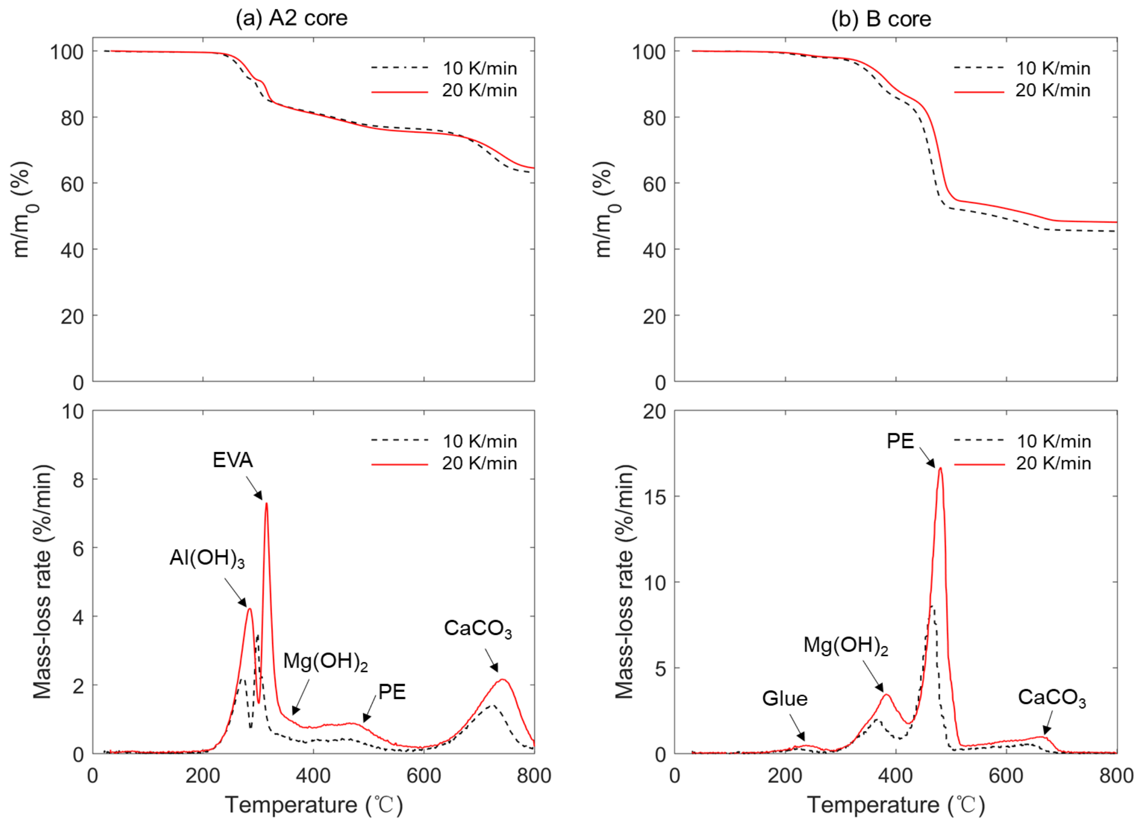

Fig. A1 TGA results of (a) A2 core and (b) B core under the argon gas flow and heating rates of 10 & 20 K/min.

For these two panel core materials, there are several local peaks of the mass-loss rate at different temperatures due to the evaporation of glue and the thermal decomposition of $Al(OH)_3$ (180-200 °C) [71], $Mg(OH)_2$ (~330 °C) [71], PE (~370-450 °C) [72], ethylene-vinyl acetate (EVA at ~350 °C), and $CaCO_3$ (~750 °C) [73]. Comparatively, A2 core material has more fire retardants and less flammable PE than the B2 core material. The total mass loss of A2 core (<40%) is also smaller than that of B core (about 55%). Both material-level aspects suggested that the B core is more flammable than the A2 core.

Based on the principle of oxygen calorimetry, the heat release rate per unit area (HRR) can be calculated to quantify the flame intensity and the fire hazards. Fig. A2 shows the HRR evolution of A2-core and B-core ACPs under two different irradiations of 40 kW/m^2 and 50 kW/m^2, where the ignition and flame extinction moments are highlighted. Once the core material is ignited, the heat release rate dramatically increases and subsequently reaches its peak value. Afterward, the flame intensity gradually decreases and eventually extinguishes after several minutes. Then, the fire is sustained in the form of smoldering combustion until burnout. Compared to A2-core panel, B2-core panel has a larger peak HRR and a longer ignition time, but the flame can sustain for a shorter period (see more detailed comparisons in Fig. 5).

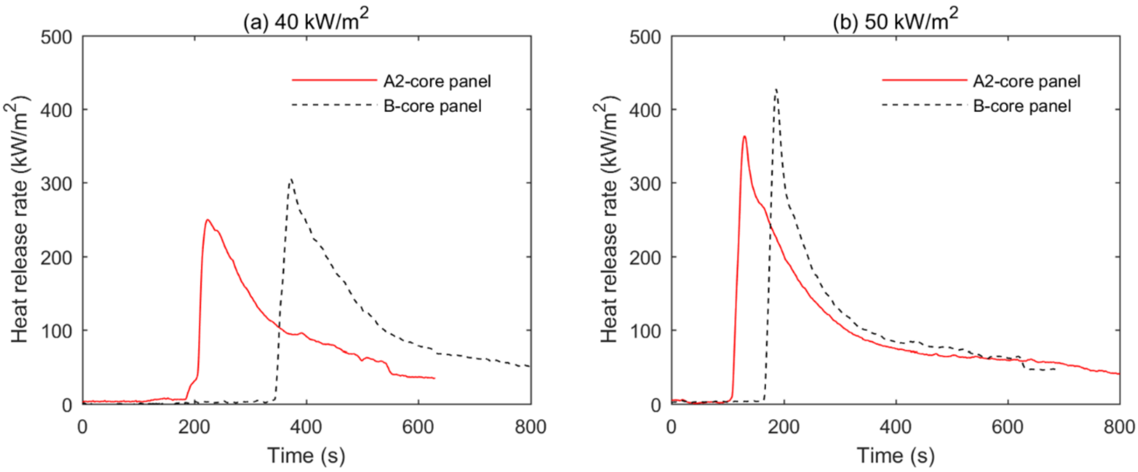

Fig. A2. Heat release rate evolution of A2-core and B-core panels under two external irradiations of (a) 40 kW/m^2 and (b) 50 kW/m^2.