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Review on the fire safety of exterior wall claddings in high-rise buildings in China

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Abstract

In recent years, several major fires occurred in high-rise buildings involving rapid fire spread upon the exterior walls and facades, and caused severe damage and loss. The extensive use of combustible insulation materials without proper fire protections and barriers were believed to contribute to the uncontrollable fire spread in the high-rise buildings. This paper reviews the current code and standard environment regulating the fire safety of exterior wall claddings in China. Three high-rise building fire cases involving rapid exterior wall fire spread are also discussed by analyzing the fire causes, propagation mechanisms and problems. The recent research progress and regulation development on the fire protection of exterior wall claddings are also presented. It was suggested that limiting the combustibility of insulation materials used in the exterior wall cladding associated with building heights, as well as proper fire protections and barriers would provide acceptable fire safety performance of exterior wall claddings in high-rise buildings.

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Keywords: High-rising building; Exterior wall; Cladding; Fire spread; Code and standard

1. Introduction

China's economic growth and urbanization has prompted a construction boom. In dense cities, such as Beijing, Shanghai and Guanzhou etc., more and more high-rise buildings and super high-rise buildings are constructed with great popularity because of high land cost. These skyscrapers normally feature modern and aesthetic appearances, as well as green and sustainable concepts. However, the new architectural features and the use of new materials have given new challenges to fire safety design. For instance, the use of combustible exterior wall cladding systems has been largely increased, because the systems have great advantages to reduce energy consumptions. However, this raised concerns of the risk of fire spread via the facade in high-rise buildings.

Research on fire spread from the floor of fire origin to the floors above via exterior walls has been carried out for many years [1-4]. Generally, fire can spread upon a building involving external walls via three principle ways. The first is an internal spread mechanism where fire penetrates through gaps and cracks between the floor slab and the external walls (especially for curtain wall systems). The second is an external spread mechanism when the intense heat from the flames and hot gases projecting out of lower openings ignites the combustible materials on the upper floors. The third is also an external spread mechanism which involves burning and fire propagation along the exterior wall assemblies.

In China, several fire cases involving extreme fire spread upon exterior combustible claddings have occurred in recent years, and caused serious property damage and life loss [5-9]. The fire safety of exterior wall claddings has attracted not only public's eyes and but also fire safety researchers' attention. In those fire cases, the fire ignited the external wall claddings from external fire sources rather than from flames and hot gases projected from windows, unlike a normal

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development progress. Once the claddings started to burn, the fire exhibited spread mechanisms in which the fire could not only spread upwards along the wall but also spread downwards due to aspects of the insulation materials (e.g. thermoplastic). As a result, severe losses from the fire cases shocked the public and fire safety researchers.

Thereafter, it was realized that fire safety features of exterior wall claddings should be considered very carefully, especially for high-rise buildings. A series of research efforts have been devoted to study the fire performance of exterior wall claddings for high-rise buildings, including combustibility of insulation and cladding materials, and how to implement safety measures, like fire protection and fire barriers, in facades.

This paper presents a review of the code and standard requirements on the fire safety of exterior wall claddings in China. The causes and spread mechanisms of three real fire cases occurred recently are also analyzed. Moreover, recent research progress and new regulation development in order to improve the fire performance of exterior wall claddings are also discussed in this paper.

2. Requirements for exterior wall claddings

2.1. Combustibility of building materials

Reaction to fire performance is one of most important fire performance properties of a construction material. In China, this reaction to fire performance is also known as combustibility. In general, the combustibility is required for all building materials, including insulation and other materials used in exterior wall claddings.

Traditionally, building products were classified to four different classes in terms of the combustibility according to the Chinese standard GB 8624-1997 [10]. The test standards specified in GB 8624-1997 were developed originally based on DIN 4102 [11]. The four classes were A, B1, B2, and B3, also known as non-combustible, difficult-combustible, normal-combustible, and easy-combustible in Chinese, respectively.

The GB 8624-1997 had been successfully accepted and adopted in many codes and standards in China, till the new GB 8624-2006 [12] was developed to replace it. The GB 8624-2006 has 7 classes, which is based on the European classification system EN 13501-1 [13] for reaction to fire performance of building products, including class A1, A2, and B to F. However, the old classification system GB8624-1997 had been used for many years and deeply connected with many other codes and standards. Given that long cycles are needed to update all the codes and standards in association with GB8624-1997, it was believed that it would take years to complete an entire shift to the new classification system. That means both systems would co-exist for quite a long time.

By comparing the classes of various building products tested using the two classification systems, a correspondence table was presented to make quick and simple converting between the two systems, shown in Table 1. It has to be mentioned that the table only gives an overview of the two systems for some tested products and cannot be used for all products. To determine the combustibility class of a certain product, standard tests must be performed according to the certain classification system.

Table 1. Combustibility classes in GB 8624-1997 and GB 8624-2006

Combustibility	GB 8624-1997 System Class	GB 8624-2006 System Class
Non-combustible	A	A1
		A2
Difficult-combustible	B1	B
		C
Combustible	B2	D
		E
Easy-combustible	B3	F

2.2. Fire design code GB 50016 [14] and GB 50045 [15]

In China, two fire design codes apply to different types of buildings with different height limits. GB 50016 [14] covers one-storey and multi-storey building, e.g. residential buildings with height no more than 9 storeys and public buildings with

height less than 24 m, while GB 50045 [15] covers high-rise (tall) buildings, e.g. residential buildings higher than 9 storeys and public buildings higher than 24 m.

Both codes have requirements on the fire resistance rating (FRR) for exterior walls in order to be treated as fire compartmentation. The combustibility of the exterior walls is also stated in the codes, see Table 2. For multi-storey and tall buildings, the combustibility of load bearing and non-load bearing exterior walls is class A (or non-combustible). However, the FRR and combustibility requirements apply to exterior walls, but do not apply to exterior wall claddings like the Exterior Insulation and Finish System (EIFS) and other type of insulation systems.

In addition to the FRR requirements of the exterior walls, the two codes also require spandrels and horizontal perimeteric fire stops to prevent vertical fire spread from the projected flame and smoke from openings. The height of the vertical spandrel shall be not less than 800 mm, constructed of non-combustible materials with a fire resistance rating of at least 1.0 h. And for curtain wall systems, gaps at the horizontal perimeter of the floor slab shall be treated with proper fire stops to prevent penetration and fire spread.

Table 2. Height limit, FRR and combustibility requirements in GB 50016 and GB 50045

	Code Applies	Class	Height (<i>H</i>) or Storey(<i>S</i>)		FRR and Comb. Requirements for			
			Residential	Public	Load bearing exterior walls		Non-load bearing exterior walls	
					FRR	Comb.	FRR	Comb.
Tall buildings	GB 50045	I	$S \geq 19$ str.	$H \geq 50$ m	2.0	A	1.0	A
		II	10 str. $\leq S \leq 18$ str.	$24 \text{ m} \leq H \leq 50 \text{ m}$	2.0	A	1.0	A
One-storey & Multi-storey buildings	GB 50016	I	$S \leq 9$ str.	$H \leq 24$ m	3.0	A	1.0	A
		II	$S \leq 9$ str.	$H \leq 24$ m	2.5	A	1.0	A
		III	$S \leq 5$ str.	$S \leq 5$ str.	2.0	A	0.5	A
		IV	$S \leq 2$ str.	$S \leq 2$ str.	0.5	B1	/	B2

3. Real fire cases

3.1. Television Cultural Center Fire (TVCC), Beijing, 2009 [5, 6]

The Television Cultural Center (TVCC) fire burned at night on February 9, 2009, which was the last night of the Chinese New Year's celebration. One firefighter dead and seven people were injured. The TVCC building is owned by China Central Television (CCTV) and built adjacent to the CCTV headquarters, shown in Fig 1. The building was not yet completed at the time and not occupied.

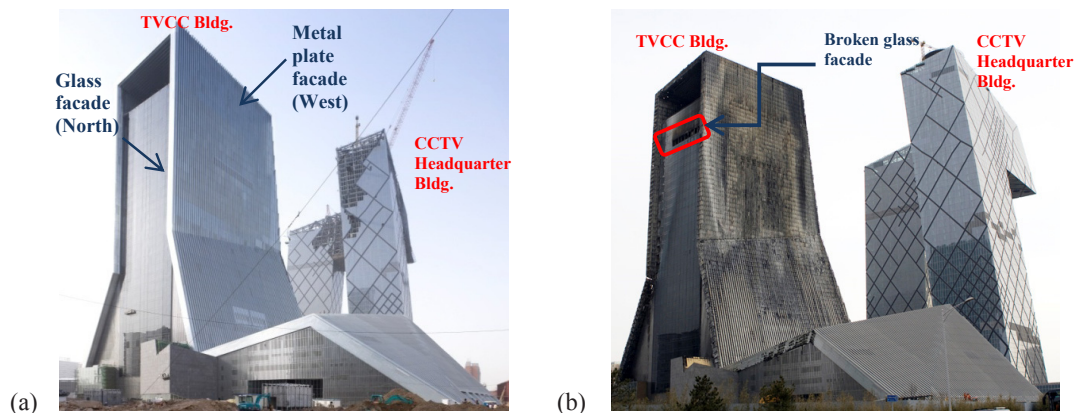


Fig. 1. (a) The TVCC building before fire; (b) the TVCC building after fire.

The TVCC tower is 159 meters high (32 storeys) and comprises three structures: a main tower in the center and two angular wings that branch off the tower on the east and west side, shown in Fig. 1(a). The main tower, with an atrium in the center located from 5th floor to 26th floor, was to house a restaurant and a hotel. The tower's northern and southern facades were installed with glass curtain walls, while the east and west claddings featured metal panels and strips made with titanium-zinc alloy.

The fire was initiated on the roof by fireworks. The high temperature particles from fireworks landed on the west part of the roof, penetrated the metal panels, and ignited the insulation materials and water proof sheets underneath the panels. The titanium-zinc alloy was reported to be able to melt at about 400 °C. The water proof materials were EPDM rubber sheet and the insulation was Extruded Polystyrene (XPS) foam. Cavities exist between the metal panels and the insulations.

The fire started to spread on the roof to the east and west sides. It was reported that, when the fire reached the roof edges, the melting and burning drops of XPS flew down through the facades. The fire then propagated to the lower floors. Fed by high winds, the fire spread quickly and the tower was completely engulfed in flames within less than 20 min.

The fire also spread into rooms because some of rooms had been partially furnished and decorated. The fire and smoke entered the atrium in the main structure. The 20-storey high atrium enhanced the smoke movement, and the smoke with high temperatures and pressures caused breakage of the glass facade on the upper floors to allow the smoke to vent out, shown in Fig. 1(b). Fortunately, most of the glass facade was intact because the rooms were not fully furnished throughout, and therefore the interior fire did not have enough fuel to produce any severe propagation and damage in the structures.

Building fires normally spread from lower floors to upper, or from internal to external. The TVCC fire exhibited totally different spread patterns. The fire developed initially on the roof and spread from upper floors to lower and from external to internal. The extensive use of combustible insulation and large cavities without stops are believed to contribute to the fast spread. The melting and dropping feature of the XPS insulation (thermoplastic) helped to accelerate the downward fire spread. The striped panels also contribute to intense burning of the facade.

3.2. Residential Building Fire, Shanghai, 2010 [7,8]

On November 15, 2010, a fire occurred in a high-rise residential building in Shanghai, killed 58 residences and injured 71. The building, constructed in 1997, is a steel-reinforced concrete structure with 28-storey high. Fig. 2(a) shows the fire building and the adjacent buildings. When the fire occurred, the three high-rising residential buildings were undergoing renovation for installing exterior wall insulations, and the buildings were covered by steel scaffolding around the structures. The scaffolding was decked with wood and bamboo plates to allow workers to walk on and operate. Moreover, the scaffolding was wrapped with nylon netting to prevent falling of construction materials.

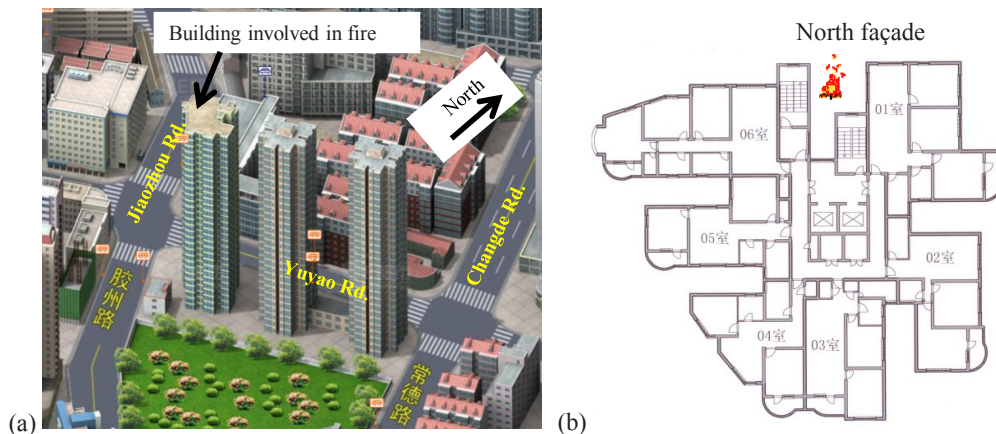


Fig. 2. (a) The residential high-rise building; (b) the plan view of the fire building.

The fire started in an L-shape channel on the north facade between the 9th and 10th floor, shown in Fig. 2(b). Welding sparks ignited insulation (polyurethane foam) chips or pieces falling on the wood and bamboo decking at about 9th floor. The burning polyurethane (PU) foam soon ignited the decking wood and bamboo, nylon nettings as well as the insulation on the exterior wall. The external fire spread rapidly because the external envelope materials were highly flammable and with very good access to air supply. The stack effect in the L-shape channel was also considered to contribute to the rapid

vertical propagation. It was observed that within about 3 min, the flame reached the 20th and 21st floor, and it only took about 4 min for the fire to spread up to the roof. About 14 min after the ignition, the external fire almost burned out on the north facade but the fire had spread into the apartment rooms on the floors from 6th to 27th. The fire also spread onto the west and east facades along the envelope of the building.

The building was equipped with automatic sprinkler system on floors from the 1st to the 4th. The sprinklers acted when the fire spread into the internal rooms. However, this helped nothing to control fire spreading on the external walls.

3.3. Wanxin Complex Fire, Shenyang, 2011 [9]

On February 3, 2011, a large amount of fireworks were placed close to the Wanxin Complex and launched to celebrate the Chinese New Year festival. The complex buildings were ignited by the fireworks.

Newly constructed and put in use in 2009, the Wanxin Complex comprises four individual parts, three towers and a skirt building interconnecting the three towers at the base, shown in Fig. 3. The skirt building is labeled as D, which is 10-storey or 46.8 m high over the ground and 3-storey underground. Above Skirt D, sitting three towers, labeled as A, B and C. Tower A is 45-storey or 180 m high and the rooms are used as a hotel. Tower B and C are both 37-storey or 140 m high. Tower B was occupied as an apartment building while Tower C was used as an office building. The horizontal distances between tower A and B, and A and C are both 6.5 m, while the distance between B and C are 63 m.

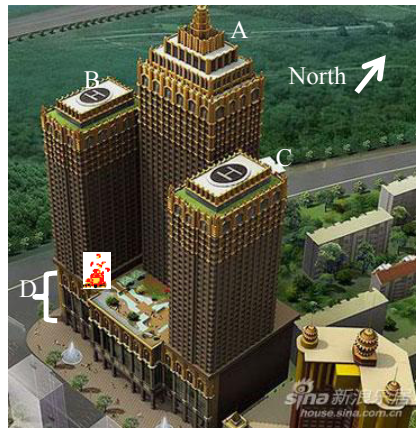


Fig. 3. The Wanxin Complex buildings.

The facade of the towers was cladded with aluminum panels and aluminum composite panels. For Tower A, Expanded Polystyrene (EPS) foam was used as insulation and the cavity between the claddings and insulation varied from 170 to 600 mm. While for Tower B, XPS was used as insulation and the cavity ranged from 190 mm to 600 mm. Investigation showed that the XPS used for Tower B was tested to have combustibility of Class B2 and the combustibility of the EPS used for Tower A was tested to be Class B1. For Tower A, the openings on the south facade directly opposite to Tower B and C were protected with fire-resistant windows and the rest of the windows were equipped with 3-layer of toughened glazing.

The fire broke out at midnight. Particles from fireworks landed on the roof of Skirt D and ignited plastic grass for decoration on the 11th floor, close to Tower B. A few minutes later, the fire spread to the exterior wall of Tower B and penetrated the surface of aluminum composite panels and ignited the XPS insulation behind. After the insulation was ignited, high temperatures caused more aluminum composite paneling to fail, enabling more insulation exposed to heat and oxygen. The fire propagated vertically very fast, and after about 15-20 min, the flame reached the top of Tower B on the south side and started to spread upon the east and west sides of Tower B. The fire also entered the internal rooms through broken windows, but suppressed by sprinklers on those lower floors in Tower B. However, the sprinkler system was unable to control a large interior burning area, because more and more rooms were ignited floor by floor. It was found that fire in the internal rooms on higher floors caused significant damage in Tower B.

At about 1 hour after the fire started, Tower A was ignited. The distance between A and B is only 6.5 m. It was believed that fire debris and high radiation heat flux from Tower B contributed to the ignition of the Tower A. The fire started to spread upon south facade of Tower A, but was successfully controlled by the fire department. The fire only spread to partial part on the east and west facades of Tower A and no burning was observed on the north facade. Tower C was not affect by the fire at all.

4. Provisional regulations on exterior wall claddings

Since the TVCC fire, questions have been raised about the fire safety of exterior wall claddings in high-rise buildings in China. Safe use of combustible insulations in high-rise buildings was taken into account with great attention and concerns. In September 2009, as a quick response to the TVCC fire, Ministry of Public Security (MPS) and Ministry of Housing and Urban-Rural Development (MOHURD) issued provisional regulations on the fire protection of the exterior insulation finishing system and decorative exterior wall materials.

The provisional regulations provided combustibility limits of using exterior insulation in high-rise and mid-rise buildings associated with building heights. Table 3 summarizes the requirements from the provisional regulations. It should be mentioned that spandrels and horizontal fire stops at the floor perimeter shall also comply with what have been required in the codes.

It shows in the table that the requirements of using combustible insulations in exterior walls with curtain wall systems are more stringent than those in exterior walls without curtain wall systems. This makes more sense because the risk of stack effect in the cavity of the curtain wall system is considered. It could potentially accelerate the fire and smoke spread in the building. For exterior walls with no curtain wall systems, the requirements in public buildings tend to be more stringent than those in residential buildings. This is because more occupants are expected in public buildings.

In addition to the combustibility requirements, the regulations also require that the insulation shall be protected on the surface from direct fire exposure, and proper fire barriers should be applied at the floor area. The thickness of protection layer on the insulation surface shall be no less than 6 mm on the first floor, while the thickness shall be no less than 3 mm on the second floor and above. If fire barriers are required to be installed at the floor area (see the comments in Table 3), the fire barriers shall be made with non-combustible materials (Class A) and the height shall be no less than 300 mm.

Table 3. Provisional regulations on using combustible insulation in exterior wall claddings

Exterior wall type	Occupant type	Height limits (H , in m)	Combustibility of insulation materials	Comment
Exterior wall with no curtain wall	Residential	$H \geq 100$ m	A	
		$60 \text{ m} \leq H < 100$ m	A, B1, or B2*	*: Horizontal fire barrier shall be installed at each floor, if B2 is used.
		$24 \text{ m} \leq H < 60$ m	A, B1, or B2*	*: Horizontal fire barrier shall be installed at every two floors, if B2 is used.
		$H < 24$ m	A, B1, or B2*	*: Horizontal fire barrier shall be installed at every three floors, if B2 is used.
	Public	$H \geq 50$ m	A	
		$24 \text{ m} \leq H < 50$ m	A, or B1*	*: Horizontal fire barrier shall be installed at every two floors, if B1 is used.
Exterior wall with curtain wall	All	$H \geq 24$ m	A	
		$H < 24$ m	A, or B1*	*: Horizontal fire barrier shall be installed at each floor, if B1 is used.

5. Research progress and code development

A series of research works have also been carried out to study the fire performance of exterior wall claddings by adopting the British Standard BS 8414-1 [16] as an investigation test method. As required in BS 8414-1, the test apparatus shall have a main wall and a wind wall. The walls are at least 8.0 m high. The main wall is at least 2.6 m wide while the wind wall is at least 1.5 m wide. The combustion chamber is located at the base of the main test wall and the fire can project through the 2.0×2.0 m opening at the base of the main test wall. The chamber is about 2.0 m wide, 1.0 m deep and 2.25 m high. The heat source is provided by wood crib fire, which is able to produce a maximum HRR of about 3.0 ± 0.5 MW. The fire is expected to provide an approximate 35 min duration of burning with a steady burning period of about 20 min.

Thermocouples are placed at the external surface and internal layers to measure the temperatures at two different heights: Level 1 and 2, where Level 1 is at 2.5 m above the top of the opening and Level 2 is at 5.0 m above the top of openings.

For the exterior wall with EIFS, different types of insulation materials in association with various combustibilities were tested, including EPS, XPS, PU and PF with different thicknesses. The thickness of the surface protection layers for the insulation was also taken into account. Moreover, the effect of horizontal fire barriers at different locations was also studied. For exterior walls with metal panels used on the facade, aluminium panels and aluminium composite panels were tested and the effect of the fire stops between the outer panels and inner insulation materials was also studied.

Based on the experimental researches, it was found that the combustibility of insulation materials and the installation of surface protection layers are two factors which play very important role on the fire spread of the exterior wall claddings using combustible insulation. The installation of horizontal fire barriers, 300 mm high non-combustible materials, was able to delay or stop the fire spread on the exterior walls with combustible insulation. The aluminium panels or aluminium composite panels could melt in high temperatures, and flame and hot gases could enter the cavity between the panels and insulation. The use of fire stops between the outer panels and inner insulation materials was found to be effective to control the fire spread in the cavity. Details of the research results will be later published in other papers.

Currently, the two codes, GB 50016 and GB 50045, are undergoing significant revising and updating. Efforts have been made to merge the two codes into one fire design code to address any inconsistencies between the two codes. The merging of the two codes is nearing completion. For the use of combustible insulation in exterior wall claddings, new requirements were proposed in the code draft by limiting the combustibility of insulation materials associated with building heights, based on the provisional regulations mentioned before and the research works recently carried out. Table 4 summarizes the proposed requirements.

Table 4. Proposed requirements in the code draft

Exterior wall type	Occupant type	Height limits (H, in m)	Combustibility of insulation materials	Comment
Exterior wall with no curtain wall	Residential	$H > 100$ m	A	
		$54 \text{ m} < H \leq 100$ m	A, or B1*	*: If B1 is used, surface protection ⁽¹⁾ shall be provided.
		$27 \text{ m} < H \leq 54$ m	A, B1*, or B2*	*: If B1 is used, surface protection ⁽²⁾ shall be provided; if B2 is used, surface protection ⁽²⁾ shall be provided, and horizontal fire barriers shall be installed at each floor.
		$H \leq 27$ m	A, B1*, or B2*	*: If B1 is used, surface protection ⁽³⁾ shall be provided; if B2 is used, surface protection ⁽³⁾ shall be provided, and horizontal fire barriers shall be installed at each floor.
Exterior wall with curtain wall	Other than residential	$H > 50$ m	A	
		$24 \text{ m} < H \leq 50$ m	A, or B1*	*: If B1 is used, surface protection ⁽²⁾ shall be provided.
		$H \leq 24$ m	A, B1*, or B2*	*: If B1 or B2 is used, surface protection ⁽²⁾ shall be provided.
	All	$H > 24$ m	A	
		$H \leq 24$ m	A, or B1*	*: If B1 is used, surface protection ⁽²⁾ shall be provided, and cavity fire stops shall be installed at each floor.

Note:

surface protection⁽¹⁾: the thickness of non-combustible protection layer on the insulation surface shall be no less than 50 mm;

surface protection⁽²⁾: the thickness of non-combustible protection layer on the insulation surface shall be no less than 30 mm;

surface protection⁽³⁾: the thickness of non-combustible protection layer on the insulation surface shall be no less than 10 mm on the first floor, while the thickness shall be no less than 5 mm on the second floor and above.

It has to be mentioned that information given in Table 4 is only used as reference for discussion in this paper. Any use of the combustible insulation in exterior wall claddings shall comply with the requirements stated in the new code when it is officially issued in the future.

6. Conclusions

Based on the review and discussions presented in this paper, the following conclusions can be drawn:

(1) The real fire cases showed that the use of combustible insulation in exterior wall claddings without proper fire barriers and protection would potentially cause rapid fire spread and severe fire damage and loss.

(2) The recent research work showed that the combustibility of the insulation used in exterior wall claddings played a very important role on the fire spread via exterior walls; installation of surface protection layer was necessary to protect the combustible insulation from direct heat exposure and would help to meet the test criteria; the horizontal fire barriers using 300 mm high non-combustible insulation was effective to delay the fire spread on exterior walls.

(3) The proposed requirements in the new code draft set combustibility limits for the use of combustible insulations in exterior wall claddings associated with building heights. These proposed requirements were developed based on lessons learned from the real fire cases, the existing provisional regulations, and research experience and knowledge generated from the recent research results. They are possibly to provide acceptable fire performance of exterior wall claddings in high-rise buildings.

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