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Building Façade or Fire Safety Façade?

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The code provisions and current test standards applicable to perimeter fire barrier systems may jeopardize architects' creative designs in the near future. As architects develop new and leading edge creative curtain wall designs, it is important to develop an understanding of how various components of the facade and the facade orientation can influence fire performance. In context of the whole building, this paper outlines a list of risk factors that may influence issues of curtain wall fire safety design and discusses the building features and occupancy characteristics that can factor into an analysis to validate a given curtain wall concept.

Introduction

Visually, it is often the goal of skyscraper architecture to define a personality or individual character through the design of any skyscraper's façade. This face or skin, wrapped to the structural frame beneath, is often key to an architect's desire to evoke our emotions, instilling a sense of grandeur as if each new skyscraper were an artist's sculpture. Indeed, a trip to any library to browse the many books on high-rise architecture or skyscrapers provides us with page after page of photographs of hundreds of towering structures, each with a face and personality as unique as the architects and engineers that imagined and designed each tower.

In recent decades the desire for taller structures and, particularly, those that are competing for recognition to be among the tallest, if not the world's tallest, is reason to review the fire safety issues related to façade or curtain wall design. Additionally, due to the creativity of architects, new and unique façade designs are continually appearing. In 2005 at the 7th World Congress of the Council on Tall Buildings and Urban Habitat (CTBUH) many unique designs were showcased with twisted facades, categorized as tordos or twisters (Vollers 2005). These unique designs veer from the more traditional continuous vertical façade surfaces of the past, often using curved surfaces and rotated floor plates that complicate the facade connections and hidden details of fire barrier assemblies. Double curtain wall systems, where two glazed walls are separated by distances of less than a meter, are being implemented. These twisted façade designs, double skin designs and other new facade creations this author has encountered pose new challenges from a fire engineering perspective. The risk of fire spread through articulated elements of the façade or vertically around the facade via the mechanism of flame leap, poses new concerns for the newest class of super high-rise structures. The concerns revolve around the issues of fire department response capabilities, reliability of sprinkler systems and associated water supplies, and the characteristics of the building and building's occupants. In this paper, the mechanisms of fire spread at the façade and the recognized fire safety considerations will be reviewed. The code provisions and current test standards applicable to perimeter fire barrier systems (installed between the façade and slab edge) will be reviewed including discussion of why developing standards may jeopardize architects' creative designs in the future. More importantly, as architects develop new and leading edge creative curtain wall designs, it becomes more critical to consider the risk factors that can impact the building's overall level of fire safety. This paper will outline the list of risk factors that may influence issues of curtain wall fire safety design and discuss what building systems and features can factor into an analysis to validate a given curtain wall's design details.

Mechanisms of Fire Spread

Our understanding of the mechanisms of floor-to-floor fire spread at the curtain wall have been established by the work of fire researchers and fire engineers dating back to the 1960's-70's, curtain wall fire testing work done in the1990's, and the continuing testing efforts of product manufacturers and testing laboratories. From a fire dynamics perspective, we know that flames emitting from an exterior window can extend higher than 5 m (16.5 ft) above the top of the window. Yokoi reported such results in 1960. One test of Yokoi's was a test room with plywood walls/ceilings and a fire load of 40 kg/m^2 (8 lb/ft^2), which is characteristic of residential occupancies and at the lower end of the fire load scale. The hot gases from the fire room window measured 400-600°C (750°-1,112°F) at 1,750 mm (5.75 ft) above the top edge of the fire room window. The glass broke out under this exposure.

Analysis of 400 fire compartment experiments (Thomas and Heselden 1972) helped to more fully explain the physical phenomena of ventilation controlled fires. Ventilation-controlled fires represent the scenario where a fire burning in a building breaks the window

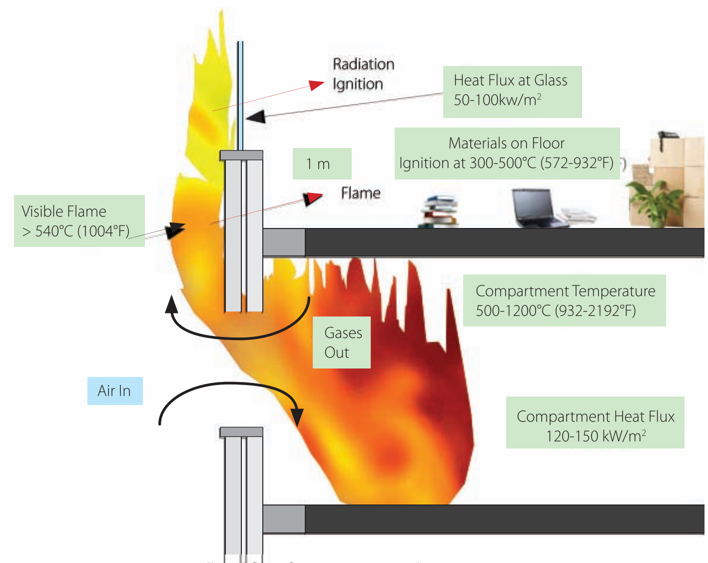

Figure 1. Exterior curtain wall and floor fire exposure mechanisms. (Schirmer Engineering, 2007)

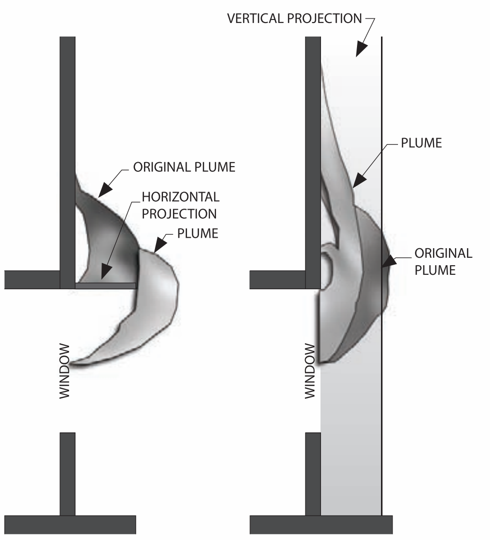

Figure 2. Impact of horizontal and vertical projections on window plume. (Oleszkiewicz Nov.1990, Fire Technology, p. 366)

glazing, permitting hot gases to flow out the top portion of the opening. A portion of the hot gases are unable to burn inside the room due to limited air (ventilation controlled) but, upon movement to the exterior, encounter sufficient air entrainment, allowing the hot fuel gases to burn outside the building. The result is a flame projecting out and upward from the window. From a visual perspective, flame extension is estimated at the point that flame temperature drops below 540 °C (1,000 °F), which corresponds to the flame no longer appearing luminous.

Taking the data of various researchers, Ove Arup & Partners was commissioned to develop a number of correlations to estimate flame projections and flame temperatures under natural or forced draft conditions (Law and O'Brien 1975). We know from this work that the fire flame projection and temperature profile will be a factor of window area and height, room geometry, fuel contents and burning rate, and wind velocity. In review, our knowledge of fire dynamics allows us to understand how the building interior areas and curtain wall can be attacked by fire in three principal ways. Figure 1 illustrates the potential temperature and heat flux characteristics of a fully developed, unsprinklered compartment fire.

The three principal mechanisms at work in Figure 1 are as follows:

- Inside – Flames and fire gases in the building attack the interior surfaces and details of the curtain wall and associated perimeter fire barrier materials.
- Outside – Flames and hot gases projecting from fire-broken glazing or other openings directly impinge on the curtain wall exterior face (convection).
- Outside – Flames projecting from fire-broken glazing or other openings radiate heat to and through glazed surfaces or through other openings to building contents and furnishings.

Exterior building detailing, articulations incorporated as elements of the facade and structural floor plate changes can all impact the flame projection and associated corrective and radiation heat exposure to the façade. Work done at the National Research Council of Canada (Oleszkiewicz 1990-91), showed the extent to which a horizontal projection located above flames issuing from a window can be effective at reducing the flame exposure. This work also showed that vertical exterior elements could have a negative impact by increasing the vertical projection of flames along a façade. Figure 2 illustrates the change in fire flame position and extension due to a horizontal projection above a window and vertical panels located at each side of a window.

> “Technology allows us to go as high as we want. For example, in the past, elevators were a challenge – but not any more.”
>
> ***Hamid Kia**, Director of Middle East Operations at RMJM Hillier, discusses how architects and engineers are attempting to break new records by raising taller and taller buildings into the sky. From “Reaching for the Clouds” by Angela Giuffrida, The Nation, June 16*

In terms of hazard reduction or increase, Figure 3 illustrates how the deflection of the flame by a horizontal projection reduces the heat transferred to the wall above the burning compartment. Conversely, the vertical projections increase the heat transfer to the wall. The increase in heat flux with vertical projections installed is due to the restriction of lateral air entrainment, which forces a lengthening of the gas plume as it seeks to entrain more air for combustion. Oleszkiewicz conducted propane fueled experiments in a three-story high facility using a window of 2.6 m width and 1.37 m high (8.5 ft x 4.5 ft) and fires on the order of 6 MW. Horizontal projections of 0.3, 0.6 and 1.0 m (approximately 1, 2, and 3.3 ft) were compared to the case of flames issued out the window along a vertical wall with no projections. Heat flux (connective + radiative) measurements taken at 1 m, 2 m, 3 m (3.3, 6.6, 10.8 ft) above the top of the window showed a significant decrease in heat flux with horizontal flame deflectors in place. For example, at the 1 m height above the window opening, heat flux ranged from approximately 50 kw/m^2 to 100 kw/m^2. However, as indicated in Figure 4 at the 1 m height, total heat flux was reduced by approximately 55 %, 60 % and 85 % respectively for projections of 0.3, 0.6 and 1.0 m. These reductions show the effectiveness of a horizontal projection. By comparison, Oleszkiewicz noted that a vertical spandrel wall was not found to be a practical means of protection against flames issuing from an opening. Achieving a 50 % decrease in heat flux exposure via a vertical spandrel panel in this same test would require a 2.5 m (8.2 ft) high spandrel. It is noted that the same performance in heat flux reduction was achieved with the 0.3 m (1 ft) horizontal projection at 1 m (3.3 ft) above the opening.

Background on Current Code Practices

Today’s codes such as the 2007 International Building Code and the National Fire Protection Association’s 2006 Building Construction and Safety Code (NFPA 5000) recognize that with a properly designed and operational sprinkler system, the threat of fire spread along the exterior of the curtain wall is effectively mitigated. This is a critical assumption that deserves further consideration in the context of super high-rise buildings and is discussed in detail later.

From a fire containment perspective, there are currently two basic ways to provide a code complying curtain wall design in fully sprinklered buildings. The most basic approach is for the curtain wall to be supported directly on the structural floor slab edge, which precludes any gap or joint condition, given that the floor slab is continuous to or extends past the building envelope. This type of installation would permit floor-to-floor glazed curtain wall assemblies in fully sprinklered buildings as shown in Figure 5. This approach is sometimes observed in high-rise building design, but it is not the most common approach for the installation and support of curtain walls. The second approach is

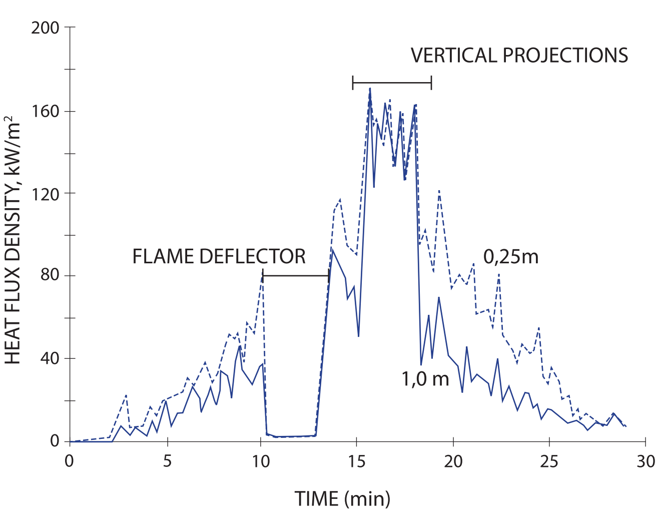

Figure 3. Decrease and increase of heat transfer for horizontal and vertical projections on window plume. (Oleszkiewicz Nov.1990, Fire Technology, p. 367)

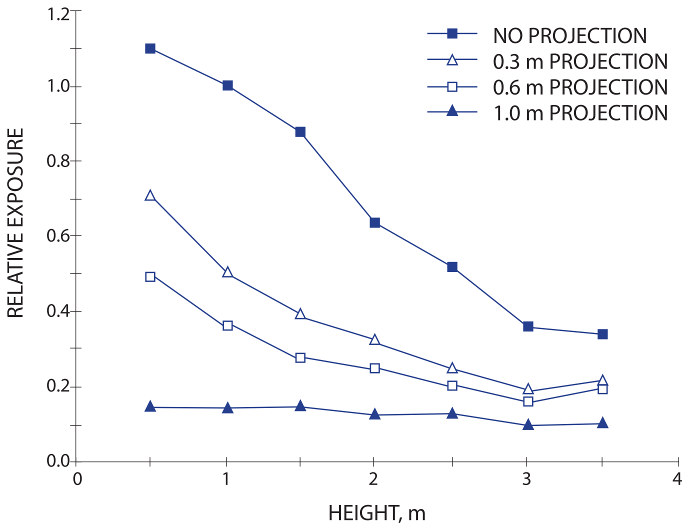

Figure 4. Heat transfer comparison of exposures for 0.3, 0.6 and 1.0 m horizontal flame reflectors. The data is normalized to readings taken at 1m above the opening with no horizontal deflector. (Oleszkiewicz Nov.1991, Fire Technology, p. 339)

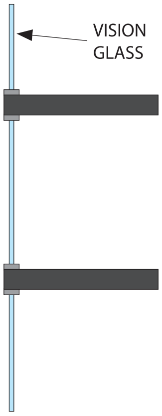

Figure 5. (left) Curtain wall supported on Slab edge. (Schirmer Engineering, 2007)

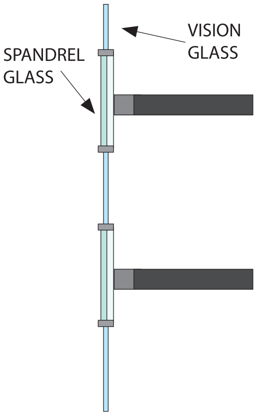

Figure 6. (right) Curtain wall hung off Slab edge. (Schirmer Engineering, 2007)

applicable when the curtain wall assembly is positioned just outside the edge of a fire rated floor system, such that a void space results between the floor system and the curtain wall assembly as shown in Figure 6.

The noted codes require that the void space at the slab edge in Figure 6 be sealed with an approved material or system to prevent the interior spread of fire (IBC 713.4, NFPA 5000 8.9.3). This requires some form of a joint system or what today are called "perimeter fire barrier systems." The basic performance criterion for these perimeter fire barrier systems is either one of the following:

1. Such material or systems shall be securely installed and capable of preventing the passage of flame and hot gases sufficient to ignite cotton waste, where subject to ASTM E119 time-temp fire conditions for a time period equal to the fire resistance of the floor assembly, or

2. Such material or systems are to be tested in accordance with ASTM E2307, "Standard Test Method for Determining Fire Resistance of Perimeter Fire Barrier Systems Using Intermediate-Scale Multi-Story Test Apparatus".

The methodology for compliance with either the criteria of item 1 above or item 2 is essentially the same, the former being the original performance intent statement which evolved into the more recent and formally defined ASTM Standard. Although a defined ASTM Standard does exist, there is confusion in the building industry among design architects and fire engineers resulting from differences in the rating criteria imposed by various testing laboratories. Underwriters Laboratories (UL) certifies perimeter fire barrier systems under the product category "Perimeter Fire Barrier Containment Systems". The systems certified by UL use the same two-story large scale fire test apparatus as are described in the ASTM E2307 Standard. However, the systems certified by UL are measured in four aspects – an F-Rating, a T-Rating, an Integrity Rating and an Insulation Rating. The ASTM E2307 Standard requires the reporting of an F-Rating and a T-Rating. This is in contrast to the F-rating which is the only requirement stipulated by the 2006 IBC and NFPA 5000 (per code change proposal.) It is important to understand these ratings and the purpose behind each rating.

F-Rating:

An F-rating evaluates the most fundamental function of a perimeter fire barrier system. The F-rating is given if the vertical passage of flame and hot gases sufficient to ignite a cotton pad is prevented by the perimeter fire barrier system. This is testing the ability of the perimeter fire barrier system to maintain fire resistance in the void space between the interior surface of the curtain wall assembly and the floor slab edge. The F-rating is expressed in hours (e.g. 2 hours) for comparison to the fire resistance rating of an associated floor assembly.

T-Rating:

A T-rating evaluates the extent of temperature increase on the non-fire side of the perimeter fire barrier system. The temperature measurements are taken at a point 25.4 mm (1 in.) or less above the fill materials perimeter fire barrier system. A T-rating is expressed in hours for perimeter fire barrier systems that do not show a temperature rise of 181°C (325 °F) for any individual thermocouple, or a temperature rise of 139 °C (250 °F) for averaged thermocouple points (required for wide voids). T-ratings are typically on the order of 0, ¼ and ½ hour.

Insulation Rating:

This rating provided under the UL certification process is similar to the T-Rating per the ASTM E2307 procedure; however, UL additionally evaluates the temperature rise on the unexposed interior surface of the curtain wall assembly above the fill materials. This is intended to determine if fire can spread to a floor above through the curtain wall construction and not just the fill material of the perimeter fire barrier system. Insulation ratings are typically on the order of 0, ¼ and ½ hour.

Integrity Rating:

This rating provided under the UL certification process is similar to the F-Rating per the ASTM E2307 procedure; however, UL additionally evaluates if there is any flame passage or surface flaming on the interior surface of the curtain wall assembly above the fill materials. In addition, the glazing above the fire exposed floor is monitored to determine when the glazing breaks. The intent of monitoring the glazing integrity is to identify how long in hours the curtain wall glazing will survive, resisting the fire leapfrog that has been observed to occur in multi-story buildings.

The F-Rating and Integrity Rating are sometimes interrelated in that a perimeter fire barrier system will not be capable of achieving an F-Rating if the curtain wall does not maintain integrity and allows the perimeter fire barrier system to become dislocated or displaced during the fire test. This is generally the case for fully glazed curtain wall systems that incorporate glazed insulated spandrel panels. The failure mode for such assemblies occurs if the spandrel glazing and framing members are not sufficiently insulated.

Under these conditions, the perimeter fire barrier system fill materials will fall out of place when the glazing panel and associated insulation fail to maintain a compression fit with the fill materials of the perimeter fire barrier system. This has often resulted in confusion and frustration for architects desiring to use full height, floor-to-floor glazed openings.

Given that the 2006 IBC and NFPA 5000 codes only require the void at the intersection of the curtain wall and the floor assembly be protected with fire barrier fill materials, there is often confusion. There are no formally published tested perimeter fire barrier systems that allow for floor-to-floor height vision glazing. This is mostly an artifact of the nature of compression-fit type fire barrier methods and their integration with fully glazed curtain walls. If a tested perimeter fire barrier system could be shown to stay in-place in the void after the glazing failed, then code compliance would be achieved. Howver, the extent of the failed glazing may raise concerns for flames readily entering adjacent spaces above. This lack of such capable perimeter fire barrier systems poses a challenge to curtain wall designers/architects who wish to create façades using expansive vision glass panels.

The issue of performance expectations of non-fire rated curtain walls and the associated perimeter fire barrier assembly has been a significant item of discussion in the United States. As a result of recent code changes, it is reported (Koffel 2005) that the code intent is to recognize that if the curtain wall assembly does not have the same fire resistive capability of the floor slab, then the system protecting the void space need not perform after curtain wall integrity is lost.

Loss History

The threat of floor-to-floor fire spread at the exterior façade of any building is real and confirmed via actual unsprinklered high-rise building fires. A number of incidents have been identified in the literature (Shriver 2006, Belles 1986, Peterson 1973, Lathrop 1977, Demers 1982). The extent of fire spread in ten well known incidents has been reviewed in order to report some key observations of past incidents which are graphically represented in Figure 7.

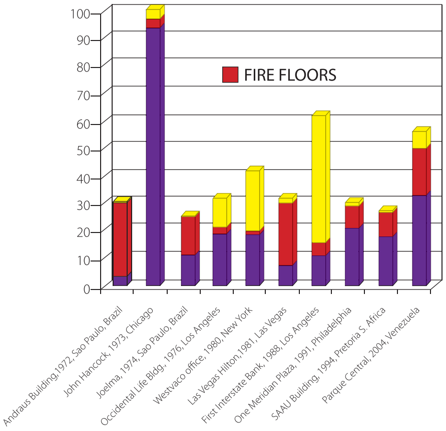

Figure 7. Fire involved floors of ten past high-rise fire incidents.

The following four summaries provide some context of the fire severity that is possible in exterior facade fire spread events. The summaries are based on information extracted from the noted references:

Andraus Building, Sao Paulo, Brazil, 31 stories, (Willey 1972):

This building was a department store occupying the basement and seven stories above grade. The 8th to 31st floors were office use. In 1972 this fire occurred on the 4th floor of the department store. The fire developed on the four floors of the department store and then spread externally up the side of the building, involving another 24 floors. The fire gutted most areas of the building. A total of 16 fatalities resulted. The building façade had extensive floor-to-ceiling areas of ¼-inch plate glass set in steel frames supported on a concrete spandrel (14.2 in. high) that was integral with the concrete floor slab. Every other section of windows was operable. From the 4th and 5th floors, the fire spread up the open stairs to involve the 6th and 7th floors. As heat broke window glass, flames broke out the north side on all four floors, forming a flame front that exposed three or four floors above the department store. The heat from exposing flames ignited combustible ceiling tiles and wood partitions on each floor. The estimated time for full involvement of the façade after flame had emerged from the department store floors was 15 minutes. Approximately 300 people fled to the roof top heliport and were eventually rescued by helicopters. Fire department response involved 28 pumpers, numerous tank trucks, and four aerial ladders.

First Interstate Bank Building, Los Angeles, CA, USA, 62-story office building (Klem 1988):

In 1988 this fire started on an office floor, and by the time the fire department arrived, a significant portion of the floor was involved in flame. Fire extended to four floors before being contained after 3-1/2 hours. The building was being retrofitted with sprinklers, but the system was not operational at the time of the fire. A 3-inch void between the floor slab and the exterior aluminum and glass curtain wall was filled with thermal insulating material extending approximately 18 in. above and below the floor slab. Gypsum board enclosed the safing material above the floor slab. The insulation below the floor deck was open to a ceiling return air plenum. About 40 persons were in the building. The fire department rescued two others from the 37th floor and one from the 50th. The fire department with 64 fire companies and 383 fire fighters made a stand on the not-yet-involved 16th floor and was able to stop further spread.

One Meridian Plaza, Philadelphia, PA, USA, 30 stories (Klem 1991):
In 1991 this fire started on the 22nd floor in a vacant office in a pile of linseed-soaked rags. It burned for more than 19 hours, completely consuming eight floors. There were three firefighter fatalities, and 24 were injured. The exterior of the building was covered by granite curtain wall panels with glass windows attached to the perimeter floor girders and spandrels. Exterior vertical fire spread occurred as a result of exterior window breakage, and this was the cited primary means of fire spread. There were no sprinklers in the building up to the 30th floor, where ten sprinklers supplied by fire department pumpers are reported to have stopped fire spread. Only building staff were in the building at the time of the fire. Fire attack was hampered by heavy smoke, complete failure of the building's electrical system, and inadequate water pressure. Firefighting was abandoned after 11 hours due to risk of structural collapse.

Parque Central, East Tower, Caracas, Venezuela, 56-story office building:
In 2004 this fire started on the 34th floor and eventually extended all the way to the top of the 56-story building. There were no functioning sprinkler systems. Pumps and standpipe systems apparently were not working. Photographs show evidence of fire spread along the exterior façade. The building was unoccupied, but three employees and up to about 25 firefighters were injured. Firefighters backed by helicopters and troops battled the blaze for 12 hours before abandoning the effort due to fear of structural collapse.

Several observations are apparent upon review of the ten reviewed incidents, which point to fire risk assessment considerations.

- Large fire department manpower and apparatus response was observed in eight of the ten incidents. In two cases, One Merdian Plaza and Parque Central, the fire departments abandoned their efforts due to fears of structural collapse.

- In several incidents occupants fled to the roof of the building to be rescued by helicopters. In contrast, many of today's super high-rise buildings will not have an accessible roof to facilitate occupant rescue operations.

- Fire spread was attributable to broken windows and flame extension along the exterior facades. The number of floors involved was as few as two stories in a 32 story building, but ranged up to as many as 23 stories in three of the ten incidents reviewed.

- The value of sprinklers was observed in the One Meridian Plaza incident where ten sprinklers supplied by fire department pumpers are reported to have stopped fire spread. It is reported (Klem 1991) that the sprinklers activated as a result of heat transmission via broken windows and through the void space that existed between the floor slab and exterior granite façade, as well as heat conduction through the floor slab. As combustibles ignited at multiple locations, the sprinklers operated and extinguished the fires.

Composite or Complex Assemblies

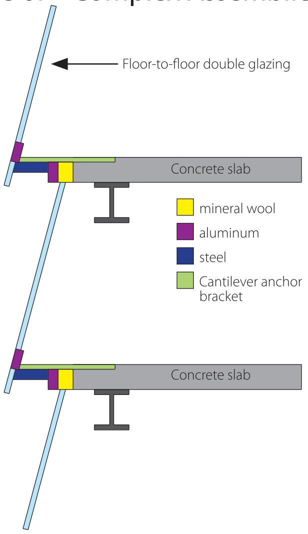

Figure 8. Hypothetical illustration of a complex constructed curtain wall assembly using an inclined glazing surface with slight bottom extension of the glazing to create a shingle effect.

Curtain Wall Components – Performance Factors

Curtain walls are a relatively complex combination of components that include aluminum frames, vision glass; spandrel panels of glass, metal or stone; metal back pans; insulation; gaskets; sealants; and anchors or connectors of steel or aluminum. Given a fully developed fire exposure in a room or space (i.e. sprinkler system out of service or failure scenario) bordered by a building's curtain wall system, it can be expected that vision glass failure will occur within minutes. Once the failure occurs and flames are extending to the exterior, the various curtain wall components and any perimeter fire barrier system are then subject to thermal forces and degradation that can result in fire spread to the floor above. The possible complexity of a curtain wall is illustrated in Figure 8. In this hypothetical case, a number of components are used to build, support and anchor the curtain wall system to the structure. Additional materials such as mineral wool are needed to provide perimeter fire barrier protection. Although it can be straightforward to design and size the components to readily fit together and form an appropriate weather enclosure, it is difficult to know how the components and attachment methods will survive a high temperature flame exposure and the resulting induced thermal expansion, particularly, when unlike materials are needed to work together. Consider that aluminum loses roughly 50% of its strength at 200°C and will melt in the range of 550-600°C. The steel component is not expected to melt, but will expand, inducing stress in other elements of the composite assembly. In Figure 8, potential flame exposure to the curtain wall components is likely exacerbated by the geometry of the inclined overlapping shingle design.

The nature of the curtain wall design will dictate the relative capability to resist floor-to-floor fire spread. Key factors that impact the curtain wall's resistance to vertical fire spread are as follows: ✍

- Full height or partial height (e.g. spandrel panel design) vision glass systems
- Nature of the glass used to construct glazing system
- Nature of the curtain wall components (e.g. framing, spandrel panels)
- Height of spandrel panels
- Vertical or horizontal projections on exterior that may deflect or enhance flame behavior
- Building geometry at curtain wall – twister, staggered, sloped, etc.
- Operable windows/openings – size, vertical or horizontal orientation
- Ability of perimeter fire barrier system to remain in void during fire exposure

When full height vision glass systems are used, flame extension and heat fluxes to the window areas above can be expected to be greater than that expected for curtain walls using a spandrel panel design. A spandrel panel design will limit the flame extension and reduce heat flux to the areas above by providing an opaque surface to block the heat transfer. To prevent the leapfrog effect using a spandrel design requires a vertical spandrel dimension of approximately four and five feet in order to match the performance, respectively, of one and two hour fire rated floors (Shriver 2006). The construction of the spandrel can be an important factor to the performance of the perimeter fire barrier system. Typical aluminum framed curtain walls using spandrel glass require that the glass be appropriately insulated using mineral wool rather than fiberglass-based insulations that will melt. Additionally, the aluminum mullions require insulation protection; otherwise the aluminum frame will melt and no longer support the wall system. These measures will help keep the glass spandrel panel and any associated fire barrier system intact. Precast panels offer the advantage of high resistance to heat exposure and offer a solid rigid surface for securely positioning or compression fitting a perimeter fire barrier system into the void between the precast panel and the floor slab edge. Metal curtain wall panels or metal back pans that, when subjected to the fire heat, may warp or distort allowing gaps to develop at the perimeter fire barrier system, and specific measures may be needed to stiffen the metal pans.

Glass used in curtain wall assemblies may be one of several types – float glass which may be heat strengthened or tempered glass, and laminated or wired glass. Vision glass can be single, double or triple glazed, and are typically assembled into an insulating glass unit (IGU). Vision glass may also be tinted to provide a heat absorbing quality, or coated to provide a heat reflective capability. All of these features can impact the performance of glass under fire exposure, however, very little is currently known about the fire performance of the wide variety of IGUs that are possible. What we do know about glass performance is limited to standard single glazed assemblies and, recently, some information on double glazed units has been presented.

Small scale tests (Kim, Lougheed 1990) have shown that plain float glass exposed to radiation at 10 kW/m^2 and 40 kW/m^2 in glass broke at temperatures of 150-175 ˚C within eight minutes and one minute respectively. In these same tests, heat strengthened and tempered glass survived 43 kW/m^2 for 20 minutes without breaking while reaching temperatures of 350 ˚C. Additional small scale tests (Mowrer 1998) showed that single glazed windows failed in the range of 40 to 50 kW/m^2, noting that 33 kW/m^2 appeared to be a level below which failure did not occur.

Of course, the ignition of materials on the unexposed side of a window is of key importance. It is important to know what quantity of radiation will be transmitted through a glass layer to combustible materials on the unexposed side, given that 10 – 40 kW/m^2 can ignite materials in the range of lightweight fabric materials to common cellulosics (Deal 1995). Again, the results of small scale tests have shown that a double glazed assembly will absorb approximately 90 % of the thermal flux and is capable of reducing heat flux from 100 kW/m^2 to 8 kW/m^2 (unsprinklered conditions.) This is significant only if the glass does not break and maintains its integrity as a solid barrier. A recent study (Shields, Silcock, Flood 2005) indicates that double glazed systems exposed to heat fluxes as high as 25-170 kW/m^2 provided much better integrity than single glazed systems. Tests using more fire resistant glass products (Manzello, et al 2007), known as SAFTI Superlite II XL and Superlite I, showed that single pane glass would fall out of the frame at temperatures of 400-500 ˚C with nearby heat fluxes measured at 50-70 kW/m^2.

This brief summary of available data suggests some limits of performance for glass breakage, fallout and reduction of heat flux to combustible materials, however, more testing to determine the performance of large IGUs is needed to better understand these fire-related performance metrics. It may be that actual IGUs may show fire performance benefits not yet understood, however, full installations with framing elements, sealants and gaskets may play a key role – positive or negative. Such full scale installations are not known to have been tested to any degree that allows for reasonable conclusions about installed performance.

Building geometry and exterior projections of the curtain wall or building structural elements can have a beneficial or negative effect on flame length extension and heat flux exposure to curtain wall elements above the fire compartment. This can be particularly important if operable windows or ventilation openings are used. Of course, any such opening can allow the unrestricted passage of flames and hot gases from a fire on a floor below into the floor above. The position of the window or ventilation opening relative to the expected flame extension is important in assessment of the leapfrog risk.

Today many unique wall designs veer from the more traditional continuous vertical façade surfaces of the past, often using curved surfaces and rotated floor plates that complicate the façade connections and hidden details of fire barrier assemblies. Such new designs can result in an orientation that

Inclined forward Curtain Wall Supported on Slab Edge

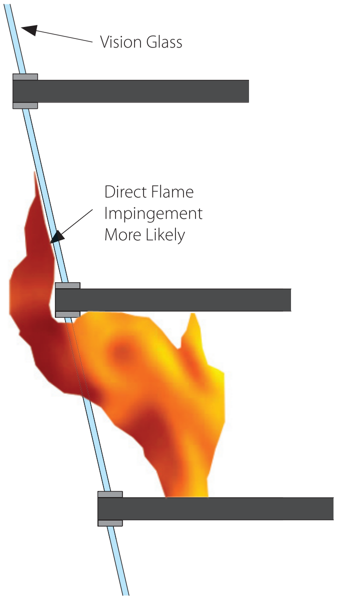

Figure 9. An inclined forward curtain wall condition can allow for more direct flame impingement and higher exposure temperatures on curtain wall components.

Inclined backward Curtain Wall Supported on Slab Edge

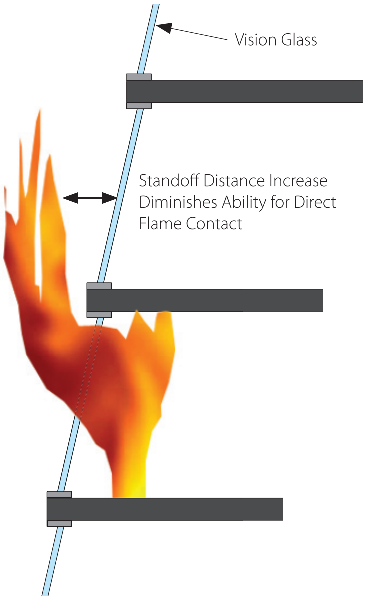

Figure 10. An inclined backward curtain wall condition can diminish the ability of flames to contact the curtain wall components.

allows for either more direct flame exposure (Figure 9) or diminishes the threat of direct flame contact (Figure 10). It is important to note that regardless of the facade orientation that wind conditions are a significant factor which may reduce or exacerbate the flame and temperature exposure.

Double curtain wall systems, where two glazed walls are separated by distances of less than a meter are being implemented. These double-skin systems intend to promote high-performance energy efficiency through the use of natural ventilation and the greenhouse effect, and may incorporate automated sun shading devices and forced ventilation concepts. The risk of fire spread through such double-skinned façades introduces new concerns arising from the fact that any flame that breaks through the inner façade is confined to within a long tall shaft-like space as indicated in Figure 11. The dynamics of the flame and radiant heat exposure for this case is expected to be more severe than a flame freely flowing to the open atmosphere.

Double Skinned Curtain Wall

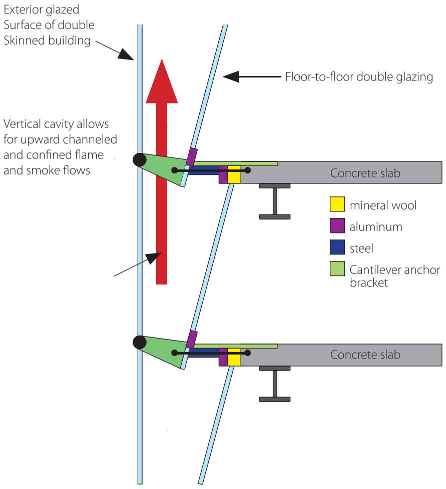

Figure 11. Double-skinned curtain wall condition showing vertical cavity which will confine and channel flame and heat vertically.

Risk Assessment Factors

Several factors to consider in a risk assessment of leapfrog fire spread at the building façade include, but may not be limited to, the following:

- Automatic Sprinkler Systems' reliability
- Fire Department/Brigade response capabilities
- Building height
- Building occupancy considerations – e.g., office, residential, hospitals, mercantile
- Building compartmentation features
- Building evacuation strategies
- Fire hazard – fuel loads, continuity of combustibles, compartment sizes
- Security threat assessment scenarios

Sprinklered high-rise buildings have a very successful record of life safety and property protection performance. For this reason, the IBC and NFPA 5000 do not require fire resistance rated spandrels or flame deflectors at the building façade in fully sprinklered buildings. There are many sources in the literature that review this successful record, however, significant reliance on sprinkler systems becomes exceedingly more critical for super high-rises. As the height of buildings increase, so does the complexity of sprinkler systems with an integrated network of piping zones, valves, pumps, power supplies, and water supply tanks. Many components are required to be operational and operated properly for the sprinkler system's success. Sprinkler system maintenance can be a major maintenance activity for today's super high-rise buildings and is key to successful performance. A recent analysis (Hall 2006) of data from the National Fire Incident Reporting System (U.S. data) indicates that for all building types, sprinklers failed to operate in 7 % of structure fires. The identified reasons for these failures were 65 % of the systems were shut off, 16 % were defeated by manual intervention, 11 % were due to lack of maintenance, 5 % of the systems were the wrong type, and 3 % were due to damaged system components. These failure rates may or may not be applicable to new super high-rise buildings, but it is important to note that human error is the primary factor. Consequently, it is important for buildings with complex sprinkler system design to have features and redundancies that can overt issues of human error and maximize sprinkler system reliability.

Sprinkler system designs can be enhanced to improve their reliability. Gravity feed systems that do not rely solely on electric pumps and emergency power supplies can assure that natural pressures are available to supply sprinklers. Also, piping schemes that use riser cross connections or feeds from alternate floors can provide additional assurances that a single closed valve does not negate sprinkler water flow. Electrical supervision of valves and other sprinkler components has long been recognized to be a most important feature to monitor sprinkler operational status. The value of sprinklers was observed in the One Meridian Plaza incident where ten sprinklers supplied by fire department pumpers are reported to have stopped fire spread after burning for 19 hours. If buildings' sprinkler systems can be designed so that successive floors cannot be turned off with a single valve, then a significant level of redundancy to protect against leapfrog can be maintained.

Fire department response capabilities need to factor into the leapfrog analysis for super high-rise buildings. Prior incidents in unsprinklered buildings demonstrate the difficulty that large, capable fire departments may have for buildings 60 stories or less in height. Consider that many of the new class of high-rise buildings will double or triple this height. An important question in this regard is, "does the local fire department have the response capabilities and response plan to handle an unsprinklered fire in a super high-rise building?" If the answer is "no," then, again, great reliance is shifted to the automatic sprinkler system.

Several basic building features and occupancy considerations that may impact the assessment of leapfrog risk are:

- Assembly occupancies - have large and potentially dense population of occupants. Often these occupancies are found at the very top levels of super high-rise buildings.

- High-rise residential – sleeping occupants in buildings generally of high degree of fire resistive construction and floor-to-floor compartmentation (except for the façade). The defend-in-place concept has been used in apartment buildings of fire-resistive construction, where it can be safer to remain in the apartment than to attempt evacuation. If the defend-in-place concept is to be viable for the wide variety of possible fire scenarios, then the leapfrog issue needs to be addressed. Human behavior has been, on several occasions, cited as playing a major role in the fatalities and injuries in high-rise residential buildings (Macdonald 1985, Proulx 1996). Both authors' works have seriously questioned the appropriateness of evacuation of high-rise residential buildings, including hotels. Frequently, occupants who stayed in their apartments or hotel rooms were safe and uninjured, while those who evacuated became casualties. In an unsprinklered super high-rise fire scenario, maintaining safe floor areas (safe from leapfrog effect) for residential occupancies could be a critical need.

- Hospital facilities – these are facilities in which occupants can be expected to require assistance from staff and are physically not capable of relocating down stairs or to the building exterior. This may be the most critical situation that deserves consideration of the leapfrog risk. Horizontal exits, where a floor is subdivided into two fire areas, are often used in hospital facilities and can be a mitigating factor in the risk assessment for hospitals or other occupancy groups.

- Super tall buildings – buildings with large occupant loads and long total evacuation times (e.g. >1 hour). In an unsprinklered super high-rise fire scenario, fire spread by vertical means, whether exterior or interior, may unnecessarily subject large numbers occupants to adverse conditions from a single fire event.

The relative fire hazard of various occupancies can present varying levels of concern in assessment of leapfrog risk. Residential occupancies are generally well compartmented units. In the event of a sprinkler failure and fire spread to a residential unit on the floor above, it should be recognized that the fire would not propagate readily due to the fire-resistive enclosure walls of apartment units. Note that this generally assumes vertical stacking of units. Conversely, in retail or office occupancy, there is far less subdivision to provide passive fire containment, increasing the risk of fire spread. Security threat assessment scenarios should consider the impact of any damage scenarios on the performance of the buildings fire protection features and, specifically, the sprinkler systems. The survivability of sprinkler system features and water supplies may be critical to prevent a major fire spread event that results from a security threat scenario.

Conclusion

Our understanding of fire and its mechanisms of spread in buildings no longer eludes us, however, the risks of fire spread related to super high-rise buildings and the facades that define their character has not been well examined. Current code practices recognize the successful record of fully sprinkler protected high-rise buildings and only require that the void space between the curtain wall and the floor slab be resistive to fire spread using a perimeter fire barrier system. These curtain wall code allowances are key to providing architects with the design freedom to design unique and creative facades.

However, the rating systems used by testing laboratories has created confusion about what type of a perimeter fire barrier system and associated curtain wall system is appropriate.

This paper has attempted to explain the laboratories' rating systems and the expected performance for tested curtain wall designs. The rating systems focus narrowly (yet appropriately) on the fire testing of specific assemblies that are not necessarily consistent with the goals of the architect, yet the larger concern is the associated risk of the fire leapfrog effect for super high-rise buildings. A review of the history of significant unsprinklered high-rise fire losses where the leapfrog effect was evident shows that the hazard is real and can be catastrophic. Key factors that impact a curtain wall's fire resistance are outlined and can be useful if there is a need to provide enhanced protection or evaluate a curtain wall assembly's potential performance when subject to uncontrolled heat/flame exposure. The most important concept is that the risk for super high-rise buildings requires the consideration of several factors that include the engineering design of the sprinkler systems, fire department response capabilities, the occupancies and associated fire loads, the building's evacuation approach, compartmentation features, and security threat assessment scenarios. With appropriate consideration and evaluation of these risk factors, it should be possible to select a curtain wall design that meets both the aesthetic goals and fire safety objectives for a super high-rise building.

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> "Don't tell anyone, but the 20th-century city is over. It has nothing new to teach us anymore. Our job is simply to maintain it."
>
> Rem Koolhaas *speaking to Nicolai Ouroussoff in New York several years ago. Whilst this viewpoint is widely shared by close observers of the evolution of cities, not even Koolhaas, it seems, was prepared for the explosion in construction in China and the Persian Gulf, where cities comparable in size to New York have sprouted up almost overnight. From "The New, New City" by Nicolai Ouroussoff, New York Times, June 8*