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PERFORMANCE-BASED FIRE ENGINEERING DESIGN: APPLICATION OF A CFD MODEL FOR THE PREVENTION OF EXTERNAL FIRE SPREAD

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ABSTRACT

The Hong Kong building code requires a 900 mm spandrel for the purpose of prevention of external fire spread from the floor of fire origin to floors above. A recent real fire in a hotel building demonstrated that the spandrel was not effective in stopping fire spread vertically. Due to natural lighting and architectural requirements, architects in Hong Kong intend to use slab-to-slab full height glazed windows for high-rise residential buildings. Horizontal projections are proposed as an alternative solution to the prescriptive code requirement for fire separation. This paper presents a comparison of spandrel performances on stopping fire spread with the horizontal projections. It was found that the horizontal projection would provide a better performance for fire separation. A CFD package, STAR-CD, was used to simulate the fire scenarios and to justify the design of the horizontal projections.

Keywords: Performance-based design, spandrel, horizontal projection, vertical fire spread, external fire spread.

INTRODUCTION

Research on fire spread from the floor of fire origin to the floors above via external walls has been carried out for many years[1,2,3,4,5]. However, application of the research results to building design is not popular, particularly in Hong Kong. From the fire protection aspect, the functions of the external walls of a building are primarily to contain a fire within the building, and to prevent entry of fire from an adjoining building[6]. When a wall has windows, however, its protective value is considerably diminished, since such openings form points of weakness for both of the considerations above. Fire safety can then be achieved by proper separation of buildings from the site boundaries. The presence of windows in adjacent storeys of a building introduces a risk of flames issuing from the windows in one storey and spreading fire through the windows above.

In general, fire can spread upward on a building via three different mechanisms for an external wall fire[1]. The first is an internal spread mechanism where fire leaks through cracks at the junction of an exterior wall and a floor. The second is a window-to-window "leapfrogging" mechanism where combustible materials inside an upper window are ignited as a result of the intense heat from flames projected out of a lower window. The third is a surface spread mechanism where fire propagates upward along the exterior wall assembly.

The first spread mechanism is unlikely to occur if the buildings were designed and constructed in compliance with the building codes. The current building codes require non-combustible materials or limited combustible materials for external walls and/or facades. The third mechanism is when fire propagates along the exterior wall assembly, which could be avoided.

The second mechanism is the major concern for fire protection design to prevent fire spread vertically. Some building codes have attempted to reduce this hazard by including mandatory structural requirements relating to the separation between openings vertically above one another. The separation usually consists of a fire-resisting spandrel wall of specified height, or a horizontal projection.

In Hong Kong, the code of practice requires a vertical spandrel not less than 900 m constructed of the same grade of fire resistance as the walls, and placed between the lintel of the lower window and the sill of the window above[7]. A horizontal projection for this purpose has not been recommended in the code of practice. However, Hong Kong Architects are keen to use full height windows with horizontal projections for office/commercial buildings and residential development to gain light and better viewing. It has been difficult to convince the approving authorities to accept the design of full height windows.

This paper presents a case study of fire separation with a 500 mm horizontal projection compared with a 900 mm spandrel. A hypothetical case, which is extracted from real projects, is adopted for analysis. A CFD model, STAR-CD, is used to simulate the fire scenarios.

FIRE SPREAD THROUGH A SPANDREL STRUCTURE

The building being considered is a 23-storey hotel with total height of approximately 97 m. Each floor has 16 guest rooms. During the late stage of construction, a room at 14/F stored a large amount of mattresses and other combustible materials. Figure 1 shows the dimensions of the room, being 3.84 m $\times$ 8.0 m with 2.9 m floor-to-ceiling height. The dimensions of the double-glazed window and the door of the room is 3.84 m $\times$ 2.0 m and 0.8 m $\times$ 2.0 m respectively. The window of each room is divided into three units such that each unit has a width of 1.28 m. The design of the hotel fully complies with the Hong Kong Building Code. The external wall of the hotel are constructed of 120 mm reinforced concrete. A spandrel (>900 mm) is placed between two floors. Both the external wall and the spandrel have at least 2 hours of fire resisting period (FRP). The double-glazed glass windows, which consist of a 100 mm cavity between 7.5 mm and 13.5 mm glasses, are fixed in the concrete wall and the spandrel.

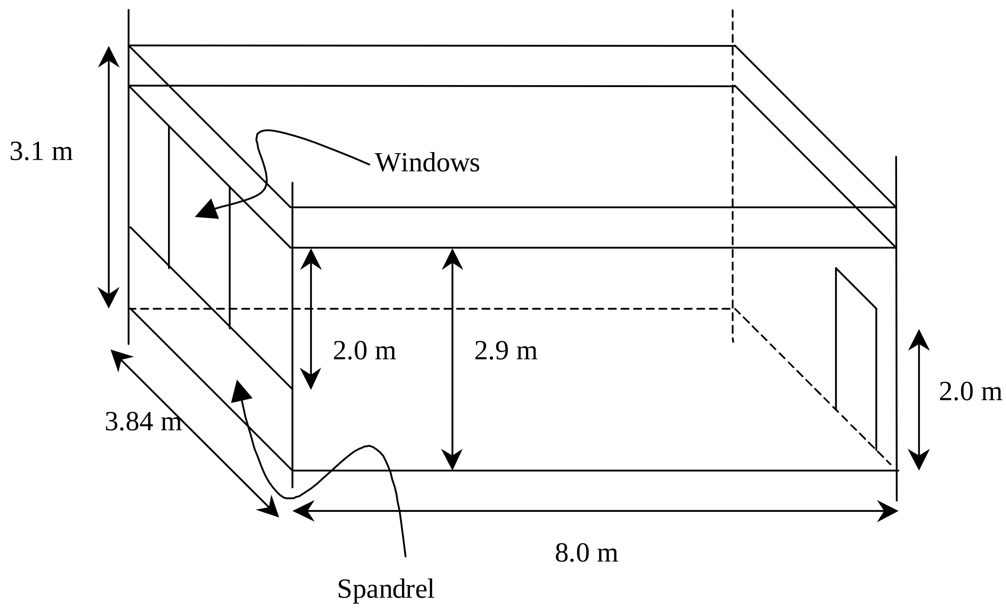

Figure 1: Dimensions of the room of fire origin.

A fire occurred and broke out in the room stored with mattresses and other combustibles at 14/F on 25th December 1998 and the fire was under control after nearly 2 hours. During the fire, the automatic sprinkler system was not in operation. The aluminium facade and the architectural fins over the room of fire origin at 14/F, to 18/F were damaged. The glass windows above the fire room at 15/F and 16/F were dislodged during this fire. The window glasses at 17/F and 18/F were cracked. Figure 2 shows the condition of the external wall during and after the fire. Figure 3 depicts the internal views of the rooms above the room of fire origin. It is indicated that a fire can spread to the upper floors through the external windows or openings even when a 900 mm spandrel is provided.

RESIDENTIAL BUILDING FULL HEIGHT GLAZED WINDOW

Description

High rise apartment and residential buildings are common in Hong Kong. Various building regulations have prescribed the requirements for prevention of vertical fire spread from floor to floor. The Hong Kong Building code requires a 900 mm vertical spandrel with a FRP, not less than the intervening floor located between two floors, and must be made of non-combustible materials.

Recently, the Authors have been involved in a high rise residential development with ancillary facilities and pedestrian linkage. The development consists of five 50-storey blocks. Due to the natural lighting and architectural requirements, the architects adopted a slab-to-slab glazing system for external walls and windows of the high rise apartment. In these cases, it is impossible to place a 900mm spandrel between two floors.

An alternative solution to the spandrel is to provide a horizontal projection or apron between the glazed windows of the two floors. The horizontal projection has not been specified in the prescriptive code in Hong Kong. To convince the approving authorities, the design process involved a detailed analysis of the performance of the horizontal projection and the spandrel with a CFD model. It is essential that the horizontal projection between the glazed windows would give equivalent or higher levels of fire separation compared with a 900 mm vertical spandrel.

In this development, there were a number of variations due to the location of the apartment block and the configurations of the flat. The design process carried out the detailed analysis for all scenarios for approval. This paper presents one typical apartment. Figure 4 shows the layout of these apartments with the slab-to-slab full height glazed walls and windows. Figure 5 shows a cross-section of the horizontal projection design.

CFD model

The STAR-CD CFD model simulated the fire in the apartment and the conditions in the open area outside the facade. Two cases will be presented in this paper. Case 1 is for a 900 mm vertical spandrel and Case 2 is for a 500 mm horizontal projection. For both cases, free boundaries were set 4 m away from the window opening, on the top and the bottom of the open area.

It was assumed that the glazed wall of the room of fire origin was fully dislodged for both cases. The purpose of this study was to investigate the differing performances of the 500 mm horizontal projection and the 900 mm vertical spandrel in stopping vertical fire spread. To ensure that the results of the two cases are comparable, it was assumed that the window of the room of fire origin was from floor to ceiling and was totally dislodged during the fire for the case of the 900 mm spandrel design.

Design fire

There are two general types of design fires in use for fire safety analysis and fire safety engineering design, namely, steady state fires and growing fires. A steady state fire is assumed to create a constant heat output from a fire once a fire starts. The fire size is estimated from the peak heat release rate of the fire (fuel controlled or ventilation controlled) or typically the value of the heat output at the time the first sprinkler activates during a fire if a sprinkler system is available in the building.

An assumption of a steady state design fire can be a very conservative approach when trying to establish realistic fire scenarios. The steady state fire ignores the fire growth period and assumes that the duration of the fire is infinite. The concept of a steady state fire has been used to design smoke extraction systems.

A real fire does not instantaneously grow to its peak heat release rate. The fire will experience a growth period. This growth period has been shown to follow a function with respect to time. This is often referred to as the t-squared fire and is represented as:

$$Q = at^2$$

where t is time (s) and a is constant. The t-squared fire formula is widely used and accepted to define the scenarios of fire growth in different situations. There are four accepted design fires in t-squared formulas, namely, ultra-fast, fast, medium and slow growth fires[8,9]. The t-squared fire formula more closely represents a real fire than the steady state fire. It was more realistic to analyse the tenability conditions and to assess the evacuation procedure using the results of the t-squared fire model.

Table 1: Constant of t-squared fire formula.

Fire type	Ultra fast	Fast	Medium	Slow
a (constant)	0.1778	0.04444	0.01111	0.002778

Ventilation Controlled Fire

As mentioned previously, the maximum fire size can be controlled either by available fuel or by ventilation (available oxygen). In this study, it was assumed that the fuel supply was unlimited, hence ventilation control is applicable. The maximum fire size in an apartment could be estimated by[8, 10]:

$$Q = 750 \times 10^3 A_o \sqrt{H_o} \quad (1)$$

where Q is the maximum fire size (W), A_o is the opening area (m^2), and H_o is the height of the opening (m).

In accordance with a general size living room, with a typical size of opening: A_o = 6.6 m^2 and H_o = 2.4 m, the calculated maximum fire size is about 7.5 MW. The result of the fire size matches with the full-scale fire tests performed in literature[11].

For CFD modelling, a fast growing fire curve with the maximum fire size of 7.5 MW was used. A constant heat output was assumed after the fire reaches its maximum. It was assumed that 30% of heat output from fire is lost by radiation. The radiation heat has been deducted during the CFD simulation.

RESULTS

Figure 6 gives the temperature distribution of the vertical section across the centreline of the living room and the glazed wall. A horizontal projection of 500 mm was installed on the external wall at the top of the glazed window. Figure 7 shows the temperature profile of the horizontal sectional view across the upper flat immediately above the room of fire origin (above the horizontal projection).

The CFD simulation results for the case of a 900 mm vertical spandrel design are given in Figures 8 and 9. Similar to the horizontal projection case, Figure 8 depicts the temperature distribution of the vertical section across the centreline of the living room. Figure 9 shows the horizontal temperature profile across the upper flat immediately above the room of fire origin.

Temperatures of the reference points on the external wall are summarised in Table 2. It can be seen that the temperature on the external wall is lower for the case of the horizontal projection than for the vertical spandrel.

Table 2: Reference temperature on external wall.

Case	Ref. point A	Ref. Point B	Remarks
Horizontal projection 500 mm	275 - 330°C	275 – 330°C	Hot smoke away from wall
Vertical spandrel 900 mm	330 - 550°C	330 – 380°C	Hot smoke close to wall

Due to the existence of the 500 mm horizontal projection, the hot plume was away from the external glazed window (Figure 7). The window was exposed to a lower radiation level compared with the 900 mm spandrel design.

It is indicated that a 500 mm horizontal projection has a better performance on prevention of vertical fire spread than a 900 mm spandrel. The Hong Kong approving authorities have approved the design of a 500 mm horizontal projection in principle, subject to a full-scale fire test.

CONCLUSIONS

It is required by the Hong Kong building code that a 900 mm spandrel with a FRP not less than the intervening floor be placed between two openings (windows) and must be made of non-combustible materials. A recent hotel fire indicated that the spandrel was not effective in preventing fire spread from the floor of fire origin to the floors above.

Horizontal projections were used for high-rise residential buildings in Hong Kong to suit the design of slab-to-slab full height glazed windows. During the design and approving process of a real project, a detailed analysis has been conducted. It was found that a 500 mm horizontal projection would have a better performance than a 900 mm spandrel. The design of 500 mm horizontal projection has been approved in principle subject to a full-scale fire test.

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A **B**

Figure 2: (A) Fire occurs at the 14th floor. The building is under construction and sprinkler system is not in operation. The room of fire origin stores mattresses and other combustible materials. (B) External wall conditions after fire.

A **B**

Figure 3: (A) Internal view of window of the room at the 16th floor. (B) Internal view of window of the room at the 15th floor.

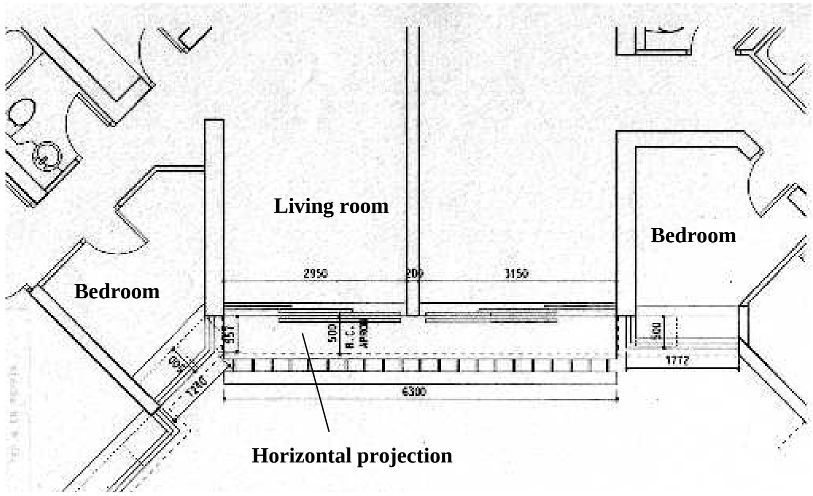

Figure 4: Layout of typical apartments with horizontal projections.

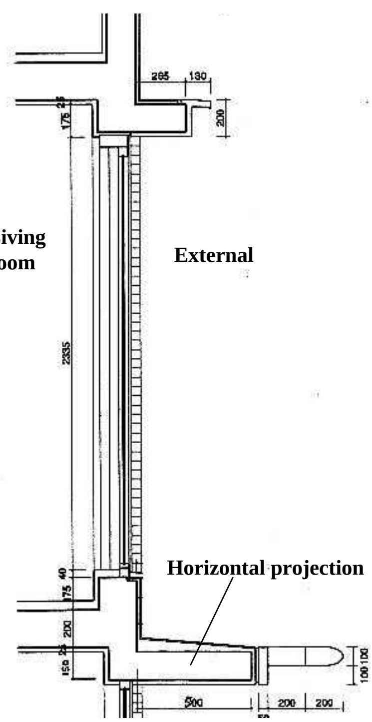

Figure 5: Sectional view of full height glazed window with horizontal projection.

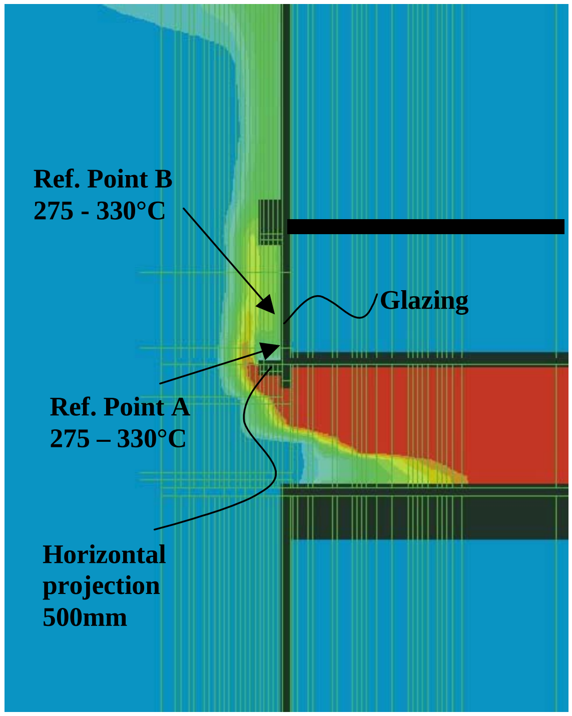

Figure 6: Vertical sectional view across the room of fire origin (with horizontal projection).

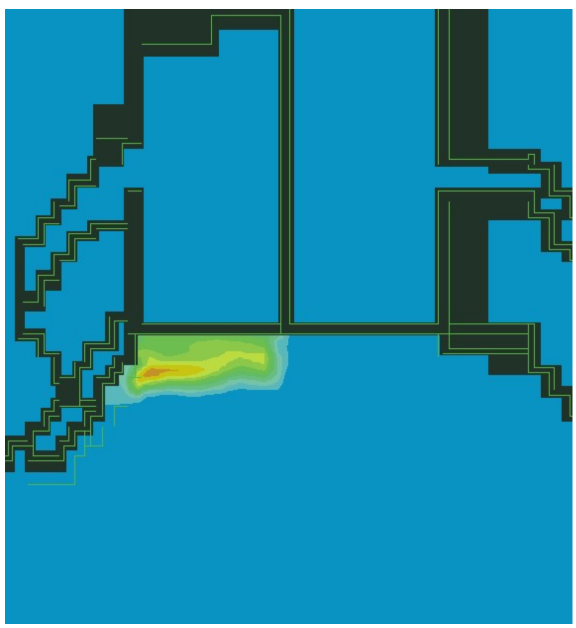

Figure 7: Horizontal sectional view across the upper flat immediate above the room of fire origin (with horizontal projection).

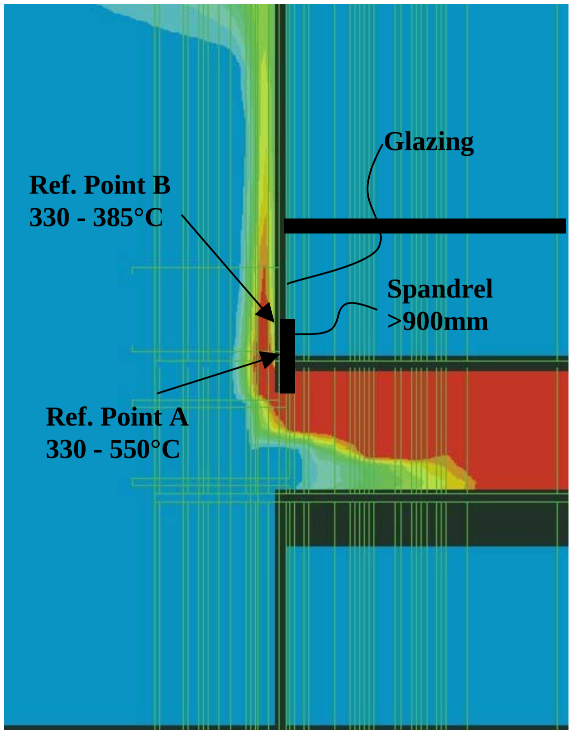

Figure 8: Vertical sectional view across the room of fire origin (with 900 mm spandrel and no horizontal projection).

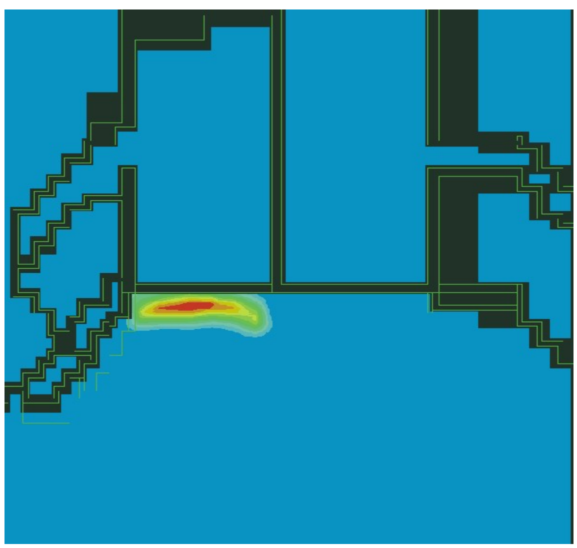

Figure 9: Horizontal sectional view across the upper flat immediate above the room of fire origin (with 900 mm spandrel and no horizontal projection).