Determining the Effectiveness of Stairwell Pressurization Systems in Multi-Story Buildings

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ABSTRACT

A ten-storey building with a stairwell pressurization system was designed according to the Australian/New Zealand Standard for The Use of Ventilation and Air Conditioning in Buildings (AS/NZS 1668.1:2015). The building was subsequently modelled in a software called Fire Dynamic Simulator (FDS) to check on the effectiveness of the pressurization system. For the system to function, the fire floor could not rely solely on building leakage but required an additional relief vent. The stairwell also required a pressure relief vent in the event of over-pressurization due to the required pressurization fan flow rate for the system to function. The system will only function as intended if the building was designed based on phased evacuation and the entry door to the stairwell on the fire floor had to shut upon completion of evacuation of that floor.

1. INTRODUCTION

As per the New Zealand legislation (New Zealand Building Code Clause C4), a functional requirement of a building is that occupants must be provided with a means of escape without being unreasonably delayed from going to a place of safety. In doing so the occupants will not suffer any illnesses or injuries. There are also performance criteria to fulfil, such as the evacuation time, not exposing occupants to certain levels of carbon monoxide, heat and ensuring visibility remains at a certain distance throughout evacuation.

Due to the increase in height and number of multi-storey buildings in New Zealand, there is a need to ensure that occupants can evacuate these buildings safely in the event of a fire. When it comes to fires, a large proportion of fatal and nonfatal fire causalities are associated with the category “overcome by smoke and toxic gases”. (Purser, 2002). As smoke is a major killer in building fires and can flow to locations that are remote (Klote, SFPE), it is important to have some form of smoke control system is in place to modify or direct the flow of smoke. There are two methods in controlling smoke movement, the first method is passive smoke control and the second method is active smoke control.

Passive smoke control is a means of restricting the flow of smoke using smoke barriers such as walls, floors or ceilings (Klote, ASHRAE). Fire barriers also act as smoke barriers. These barriers act to maintain tenable conditions on the non-fire side after ignition. However, the performance of these system depends on the construction and how any openings in these barriers are sealed. Due to the evacuation of people, doors to stairwells will be opened and any opening will compromise the performance of the smoke or fire barrier.

Active smoke control can come in the form of a smoke exhaust system or a pressurization system. The concept of stairwell pressurization is to supply enough air into the stairwell to maintain tenable conditions (Klote, SFPE). The concept is relatively simple, the higher pressure created in the stairwell should prevent the migration of smoke from the low-pressure side (Klote, ASHRAE). Although the concept is simple, there are a few components that need to be considered during the design of a stairwell pressurization system.

The first component is to do with the recommended pressure differences across the fire or smoke barrier. The minimum pressure difference is required to prevent smoke from migrating across the barrier (NFPA 92). In AS/NZS 1668.1:2015, this is shown as a minimum sustained air velocity through an open door of 1m/s excluding the ground floor discharge door from the stairs. Another component to consider is the maximum pressure difference across a barrier to allow for a side-hinged door to be opened (NFPA 101). Again, this is shown in AS/NZS 1668.1:2015 in the form of a door opening force of no more than 110N at the handle.

The second component that needs to be considered is the provision of pressure relief. The main function is to prevent the over-pressurization of the stair shaft which would make opening of doors difficult. This can come in the form of a non-mechanical or mechanical relief system. However, developing a working pressure relief system in FDS is not part of this research.

The overall objective of the research is to determine the effectiveness of designing a pressurized stairwell in a software called Fire Dynamic Simulator (FDS) using AS/NZS 1668.1:2015.

A literature review was done to generate a list of design scenarios based AS/NZS 1668. As the standard has different design scenarios depending on the classification of the building, the applicable scenarios were selected.

2. METHODOLOGY

2.1. Design Scenarios

A list of design scenarios was generated based on AS/NZS 1668.1:2015/Section 10.3 and can be found in Table 1. An office occupancy was chosen as it is one of the most common types of occupancies in a multistorey building.

The types of automatic fire alarm systems that were used in the model were the smoke detection system (SD) and sprinkler system (SPK). These typical fire alarm systems are based on the New Zealand Building Code (NZBC) Clause F7.

As per Section 10.3 of AS/NZS 1668.1:2015, the performance criteria for the system stairwell pressurization system was evaluated based on stair entry doors being open during the operation of the system.

Phased evacuation refers to when the door to the stairwell at each floor was closed after the floor evacuation time. This represented a staged evacuation where only the fire floor (FF), the floor above and below (FAB) the fire floor were evacuated before other floors. An all-out evacuation was when the doors remained open throughout the entire model run. This represented every floor evacuating simultaneously which would result in queueing in the stairwells and the stair entry doors being held open throughout the entire evacuation.

2.2. FDS Model

A fast fire was modelled in the middle of the floor based on the inputs from the Verification Method: Framework for Fire Safety Design (C/VM2). The fire has a heat release rate per unit area (HRRPUA) of 945 kW/m^2 with an area of 21.2m^2. A sprinkler controlled fast fire was modelled for the building with a sprinkler system and had a HRRPUA of 625 kW/m^2 and an area of 4m^2. Both fires were located 0.3m above the floor. The species yield of the fire was as per C/VM2/Table 2.1 for all buildings including storage with a stack height of less than 3m.

Smoke detectors for the SD case were modelled with an optical density at alarm of 0.097m^{-1} and a radial distance of 7m. Lastly, standard response sprinklers were modelled for the SPK case with a RFI of 135$m^{1/2}s^{1/2}$, a C value of 0.85$m^{1/2}s^{1/2}$, a T_{act} of 68^oC and a radial distance of 3.25m.

A mesh size of 0.2m was chosen to fit within the $D^*/\delta x$ range as recommended in the FDS Validation Guide. For the SD case, the $D^*/\delta x$ was 15.9 and for the SPK case it was 6.9.

The building was modelled with the fourth, fifth and sixth floor and two separate stairwells on opposite sides of the floor. Each floor was 50m by 50m with a floor to floor height of 3.6m, the fire floor (fifth floor) was divided into 3 separate meshes of 17m, 16m and 17m along the X-axis. A 0.6m deep floor slab was modelled to simulate a false ceiling underneath each floor as most buildings will have concealed services running underneath the floor slab. Leakage of 0.1% of the surface area of the perimeter walls for each floor was used as per C/VM2/Section 2.2.1, which amounted to 0.6m^2 of leakage per floor.

The stairs were 6.6m by 2.4m with a height of 36m. The main landing on each floor was 2.2m by 2.4m and the intermediate landing was 1.2m by 2.4m. The risers were 0.2m high to fit within the mesh size. Each stair tread was 0.4m wide. Entry doors on each level and the discharge door on the ground floor were modelled as 2m high and 1m wide. Doors on the fire floor opened after the detection system activated, plus the pre-travel activity

Table 1: List of Design Scenarios

Design Scenarios	1	2	3	4	5	6	7	8	9	10	11	12
Fire Safety System	SD	SPK	SD	SPK	SD	SPK	SD	SPK	SD	SPK	SD	SPK
Pressurization System	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Relief Venting	No	No	No	No	FF	FF	FF, FAB	FF, FAB	FF	FF	FF, FAB	FF, FAB
Evacuation Type	Phased	Phased	Phased	Phased	Phased	Phased	Phased	Phased	All-out	All-out	All-out	All-out

times and travel time from the most remote point on the floor to the entry door. Door gaps were modelled as 0.2m by 0.2m as the 10mm door gap in C/VM2 would not show up in the model due to the mesh size.
The pressurization system was modelled as an inlet measuring 1m by 1m located at the top of each stairwell. The fan was ramped up linearly over 30 seconds from the time the detector or sprinkler was activated. This was the method that adopted by BRISK when modelling pressurization fans.

The building was modelled in CONTAM (Version 3.2) to determine the fan flow rate which was used in the FDS model. CONTAM was chosen as it was an iterative software that could provide the fan flow rate quickly and was the recommended software by Klote in the Handbook of Smoke Control Engineering.

An additional relief vent of $4m^2$ was added to each floor. This vent was opened when the desired air flow through the stair door on the fire floor was not sufficient to pressurize the stair and prevent smoke flow into the stairs. Activation of the relief vent was 30 seconds after the detection system activated on the fire floor to allow for the notification timing of the system.

Velocity devices were located every 0.5m vertically in the middle of each door and a velocity plane located over each door. Pressure devices were placed at the door handle location on either side of each door. Devices measuring visibility, temperature, fractional effective dose (FED) and radiative heat flux were placed in the middle of each landing at 2m height. Devices reporting visibility, layer height, FED, temperature, radiative heat flux, upper and lower layer temperature were placed on the fire floor at 5m spacing except for above the fire where none were placed. Lastly velocity devices were placed in the middle of the relief vent along with a velocity plane across the entire vent.

Slice files were placed every 12.5m on either direction of the fire floor which showed velocity, temperature and visibility.

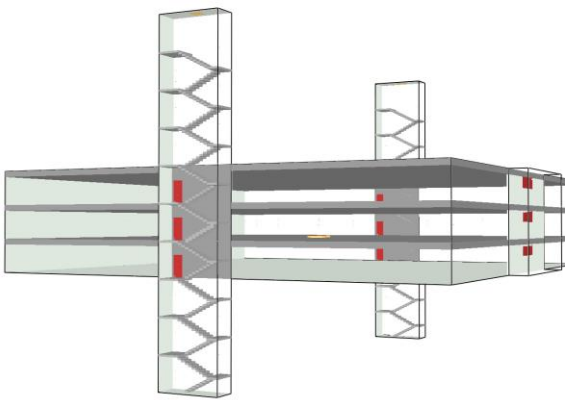

Figure 1: Picture of the Building

A picture of the building modelled is shown in Figure 1.

The version of FDS used was Version 6.5.3.

2.3. CONTAM

The entire building was modelled in CONTAM, which is a multizone indoor air quality and ventilation analysis software by the National Institute of Standards and Technology (NIST). Building dimensions, leakages and flow paths were modelled as per FDS. CONTAM was used to determine if a single inlet stairwell pressurization was possible with the building configuration and determine the maximum flow rate of the system before the force to open the entry doors into the stairwell becomes exceeded the limit specified in AS/NZS 1668.1:2005.

2.4. FDS Output

The outputs in CSV for the devices were processed using Excel by plotting the values obtained against time. The velocity through the doors was checked to ensure that when the pressurization system turned on the minimum velocity was at least 1m/s. The heat release rate was plotted and checked against a fast t^2 fire to check that the fire was inputted correctly into the model. Smokeview was used to visualize the smoke flow throughout the fire floor and in the stairwell.

3. RESULTS AND DISCUSSIONS

3.1. CONTAM

Using equation 9.4 from Handbook of Smoke Control Engineering by Klote et al, the pressure difference across the door cannot be higher than 75 Pa when using a door opening force of 110N.

CONTAM showed that with all doors closed except for the ground floor discharge door, the maximum flow rate for the pressurization system was $4.5m^3/s$ before the force required to open the top floor door went above the limit of 110N.

To achieve the minimum of 1m/s through any stair entry door in the design scenarios, the minimum flow rate required for the pressurization system was $8m^3/s$. CONTAM also showed that with $8m^3/s$ flow rate, there was still some flow into one of the stairwells of $0.05m^3/s$. As the flow rate into the stairwell increased, the amount of flow into the stairwell from the fire floor decreased. This decrease in flow into the stairwell was not significant as it did not reduce significantly at higher flow rates. Therefore, $8m^3/s$ was used in the FDS model as the flow rate for all the design scenarios.

3.2. Heat Release Rate (HRR)

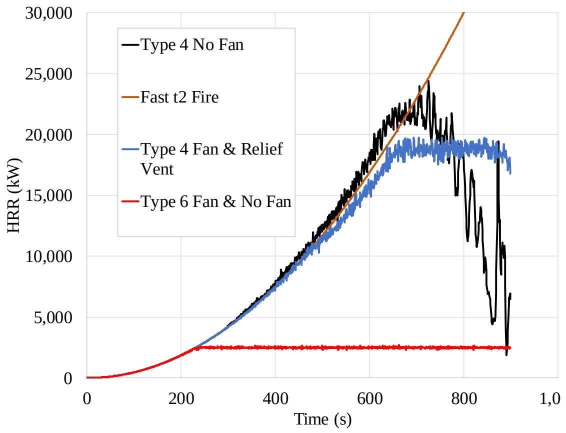

Figure 2: HRR Graph

Figure 2 shows the HRR graphs from the FDS models. The HRR graph for non-sprinklered fire without the pressurization system appeared to have some instability. This instability was due to the lack of oxygen on the fire floor over time as observed by the erratic decrease in the HRR pass 700s.

With the pressurization system turned on and the fire floor relief vent opened upon detector activation, the HRR held steady pass 600s. However, the HRR was below the maximum limit of 20MW as stated in C/VM2. This could again be due to the limited supply of oxygen on the fire floor.

Lastly the HRR for a sprinkler-controlled fire held steady at approximately 2.5MW. This was the HRR for the fire upon activation of the sprinkler system.

3.3. Fifth Floor Stair Landing Visibility

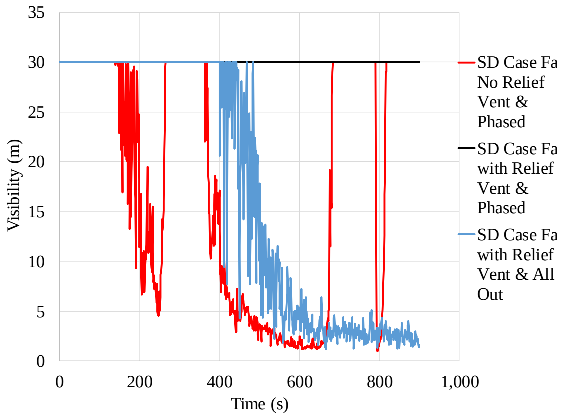

Figure 3: SD Case Visibility Graphs

Figure 3 shows the visibility of the stair landing just outside the fire floor stair entry door. When the stairwell was pressurized without a relief vent on the fire floor, visibility in the stairwell was compromised at approximately 150s as shown by the red line. Therefore, the design of a stairwell pressurization system must consider the flow path of air from the stairwell into the fire floor and subsequently exhausted from the fire floor.

This was evident as observed in the black line in Figure 3 when a relief vent was inserted into the fire floor and opened 30 seconds after detector activation. The pressurization system was able to prevent smoke flow into stair landing for a phased evacuation. However, the system failed to function as intended when an all-out evacuation scenario was used as shown with the blue line in Figure 3. This scenario was considered in the unlikely event that a building wide alarm sounded, and occupants did not follow the instructions given to allow for the evacuation of the fire floor first before evacuating the other floors.

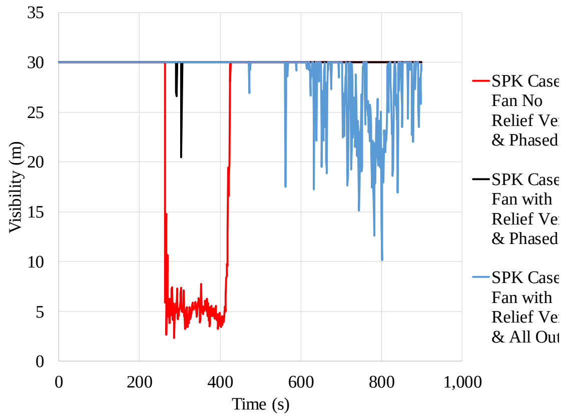

Figure 4: SPK Case Visibility Graphs

Figure 4 shows the visibility of the stair landing just outside the fire floor entry door a the SPK cases. For the SPK case and no relief venting on the fire floor, a similar result was observed as shown with the red line in Figure 5 where visibility on the stair landing was again compromised. With a relief vent and phased evacuation, the visibility was not compromised as per the black line in Figure 4. Even with an all-out evacuation, the pressurization system managed as shown by the blue line.

The FDS models ran for only 900s, which was half the expected time that was required to empty out the building. The models still showed that with a sprinkler system, the stairwell was unlikely to be compromised even at 1800s as the visibility in the stairwell recovered. The models also showed that the stairwell will be compromised with a smoke detection system in the building as there would be no system in place to control or extinguish the fire.

3.4. Pressure at the Top Floor

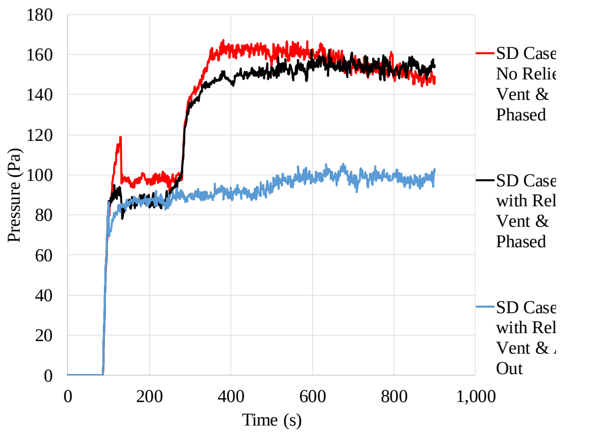

Figure 5: SD Case Pressure Graphs

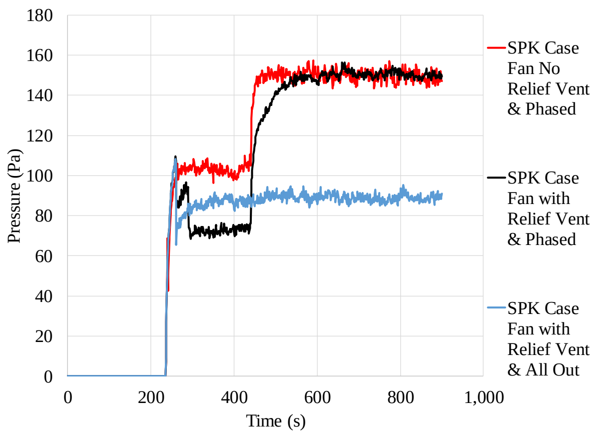

Figure 6: SPK Case Pressure Graphs

Figure 5 shows the pressures outside the top floor stair landing for the SD case. With phased evacuation shown by the red and black lines, the pressure at the top of the stairs was above the limit of 75 Pa to open those entry doors. However, if the stair doors were left open throughout the entire evacuation as shown by the blue line, there would not be an issue with opening any doors as the pressure at the top floor was around 70Pa when the doors opened. This behaviour can also be observed in Figure 6 which show the pressures at the top floor stair landing for the SPK case.

The initial spike in the stairwell pressure at the top floor may not be an issue depending on the location of the fire floor. In the model, the fire floor was the fifth floor which had a pressure of no more than 50 Pa when the doors were opened. Although there were periods of time when the pressure at the top floor for both detection systems were above the limit of 75 Pa, this would not be an issue in a pressurized stairwell.

The design of a stairwell pressurization system would generally include a pressure relief vent (mechanical or natural) in the stairwell itself. The current limited capability in FDS to model pressure relief vents meant that the vent could only be opened upon reaching a certain limit. Subsequently the vent could not be closed when it fell below a certain threshold. Therefore, the pressure relief vent was not implemented into the model.

3.5. Fifth Floor Door Velocities for the SD Cases

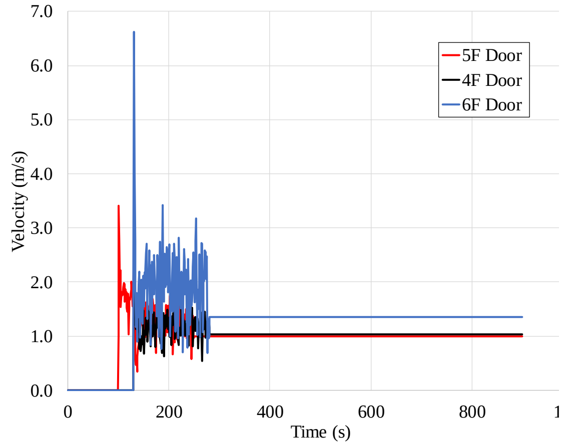

Figure 7: Door Velocity Graphs with No Relief Vent

Figure 7 shows the velocities through the doors for the SD case with phased evacuation and no relief vent activation. The minimum velocity through the doors on the fire floor and the floors immediately above and below are approximately 1m/s. However, even meeting the minimum velocity through the doors of 1m/s, the pressurization system still failed to function as intended as shown by the red line in Figure 3.

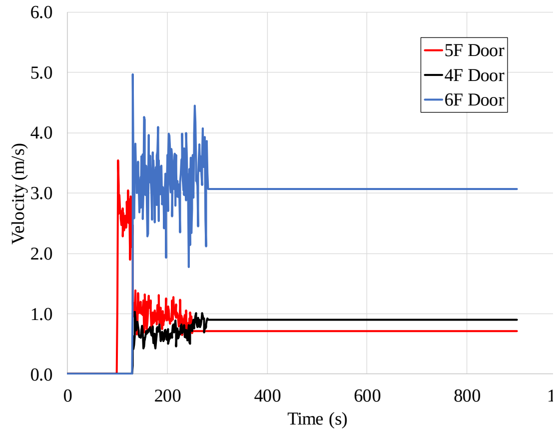

Figure 8: Door Velocity Graphs with Relief Vents

Figure 8 shows the velocities through the doors for the SD case with phased evacuation and relief vents activation. The velocity through the doors decreased as observed. With a door area of 2m^2 and a flow velocity through the doors at the sixth floor of approximately 3m/s, the flor rate though the doors at approximately 5 to 6m^3/s. With ¾ of the flow from the stairwell pressurization system entering the sixth floor, the flow rates through the lower floors decreased to 1m/s or lower. This decrease in flow rate through the door did not have an impact in the performance of the pressurization system as shown by the black line in Figure 3.

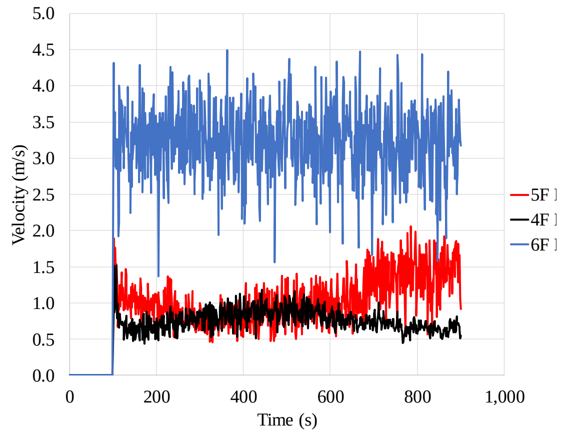

Figure 9: Door Velocity Graphs with Relief Vents

Figure 9 shows the velocities through the doors for the SD case with an all-out evacuation with relief vents activating. When an all-out evacuation strategy was employed, the stairwell was compromised (as shown by the blue line in Figure 3) due to the decrease flow rate through the doors (as shown in Figure 9) on the fire floor as shown by the red line, and increase in smoke production.

3.6. Fifth Floor Door Velocities for the SPK Cases

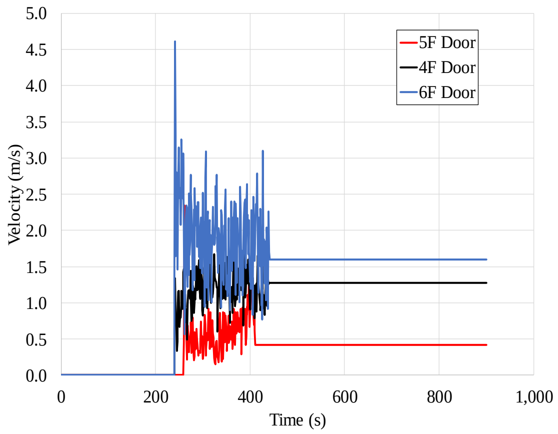

Figure 10: Door Velocity Graphs No Relief Vent

Figure 10 shows the velocities through the doors for the SPK case with no relief venting and phased evacuation. The velocity through the fourth and fifth floor doors were below the minimum of 1m/s and the system also failed to perform as shown by the red line in Figure 4.

Figure 11 shows the velocities through the doors for the SPK case with relief vents activating and phased evacuation. The velocities through the fourth and fifth floor doors were below the minimum of 1m/s (as shown by the red and black lines).

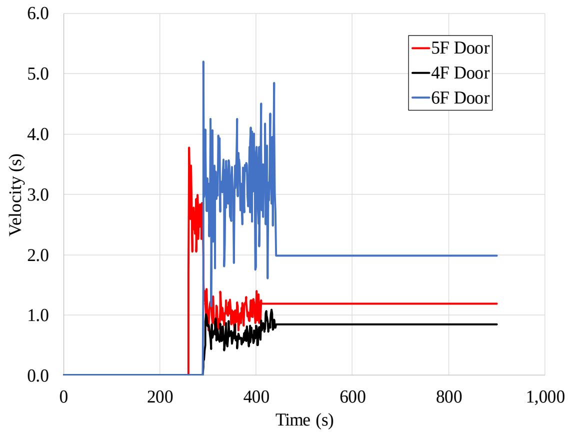

Figure 11: Door Velocity Graphs with Relief Vents

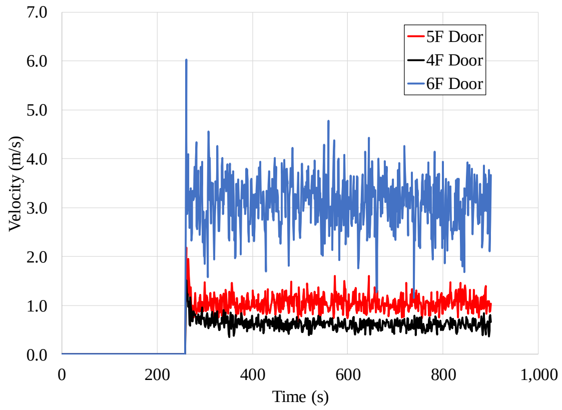

Figure 12: Door Velocity Graphs with Relief Vents and All-Out Evacuation

Figure 12 shows the velocities through the doors for a SPK case with an all-out evacuation and relief vents activating. The velocities through all the doors were constant. However, visibility in the stairwell was not compromised as per blue line in **Error! Reference source not found.** due to the sprinklers controlling the severity of the fire and hampering the production of smoke.

3.7. Relief Vent Velocities

Figure 13 and Figure 14 show the relief vent velocities for the SD and SPK cases respectively. For the relief vent velocities with phased evacuation and the SD case (red line shown in Figure 13), the velocity climbed to 2.5m/s at 100s before it dropped to 1m/s. This drop in the velocity corresponded to the doors to the floors immediately above and below the fire floor opening. The second decrease in the vent velocity corresponded to the closing of the doors on the fire floor which limited the flow rate into the floor. These events can be seen in Figure 8 where the velocities through the doors were recorded.

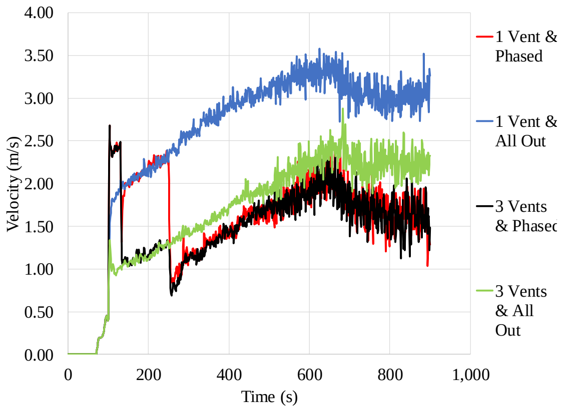

Figure 13: SD Case Fire Floor Relief Vent Velocity

Steady flow was achieved towards the end of the model run time as observed in Figure 13. The highest velocity was achieved by the model which had only a relief vent on the fire floor and an all-out evacuation strategy (as shown by the blue line). All the models had an increasing vent velocity before reaching steady flow. This was due to the increased smoke generation in the fire floor as the fire kept burning. Where only phased evacuation occurred, the vent velocity was relatively similar as the outward flow from the vent was not aided by the inflow of air from the stairwell doors being open. Whereas the all-out cases had higher vent velocities as additional air was coming in from the stairwell door due to the pressurization system running. This same behaviour was observed in the SPK cases as shown in Figure 14.

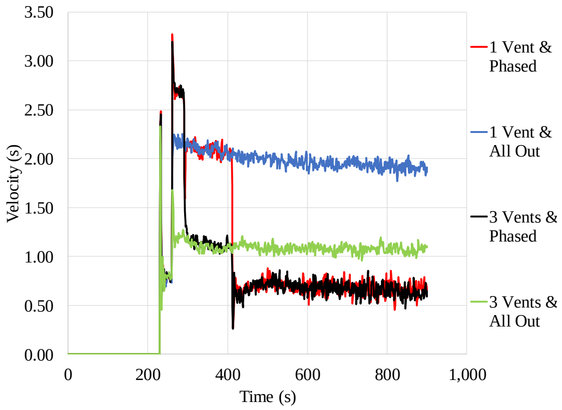

Figure 14: SPK Case Fire Floor Relief Vent Velocity

Figure 15 shows the relief vent velocities for the floors with phased evacuation. The first decrease in the vent velocity on the fire floor (shown by the red line) corresponded with an increase in the vent velocities on the other floors at 130s. When the door to the fire floor was closed, it corresponded to an increase in the vent flow to the other floors at 250s (shown by the black and blue lines). Finally, when all the other doors closed, the velocity through the other vents dropped again. The velocity for the vent on the fourth floor was relatively constant. However, the velocity through the sixth floor vent was increasing due to the inflow of smoke from the relief vent on the fifth floor as the vents were stacked directly on top of each other and the pressurization system was not flowing air into the sixth floor due to the closed door. A visual representation can be seen in Figure 17.

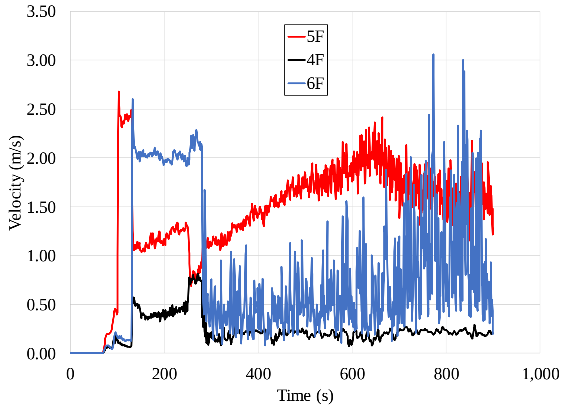

Figure 15: SD Case Vent Velocities for Three Floors with Phased Evacuation

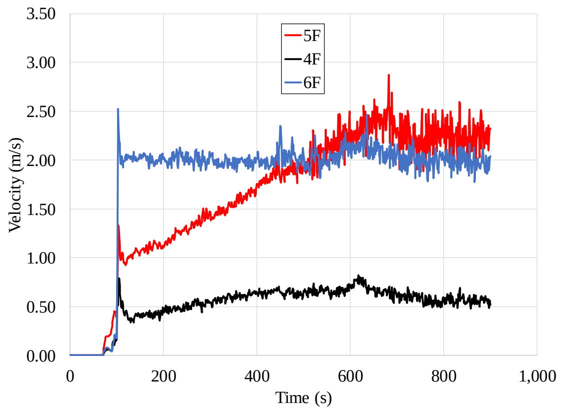

Figure 16: SD Case Vent Velocities for Three Floors with All-Out Evacuation

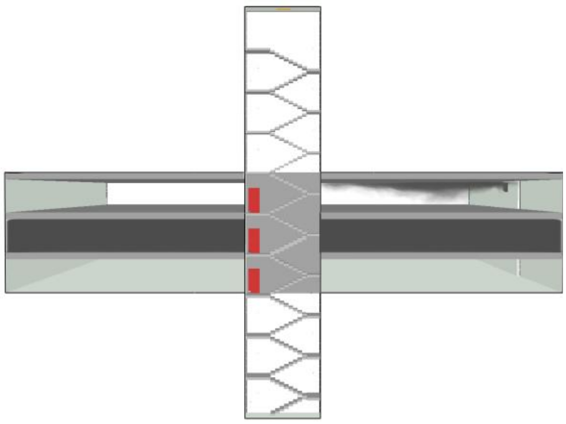

Figure 17: Smoke Flow into Sixth Floor via Relief Vent

Figure 16 shows the relief vent velocities for the SD case with an all-out evacuation. Smoke was not able to enter the sixth floor through the relief vent as the velocity through the vent was relatively constant at 2m/s.

Figure 18 and Figure 19 show the relief vent velocities for the SPK cases. The same behaviour was exhibited in the SPK case models when compared to the SD cases as shown in Figure 15 and Figure 16.

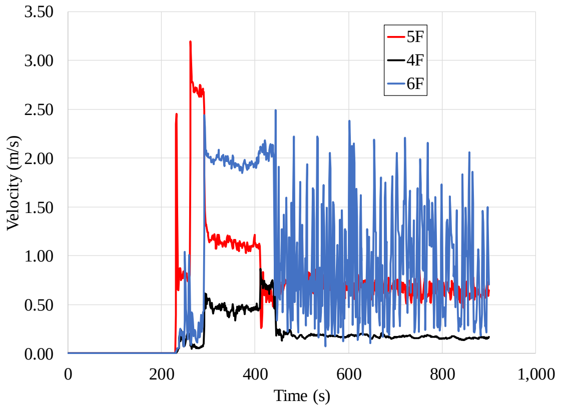

Figure 18: SPK Case Vent Velocities for Three Floors with Phased Evacuation

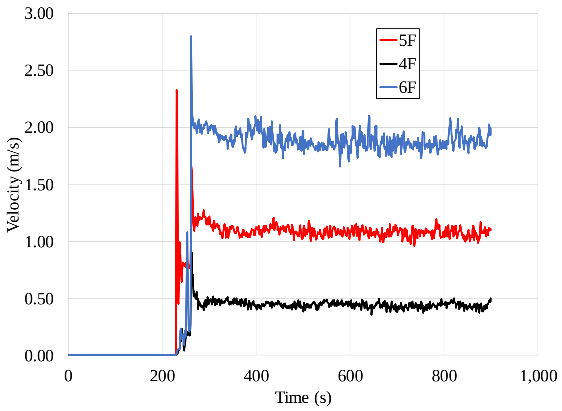

Figure 19: SPK Case Vent Velocities for Three Floors with All-out Evacuation

3.8. Visibility in the Other Floors Landing

Figure 20 and Figure 21 show the visibility for all the stair landings for the SD cases. Visibility on the landings of the other floors was not compromised for a phased evacuation. However, this was not the case for an all-out evacuation.

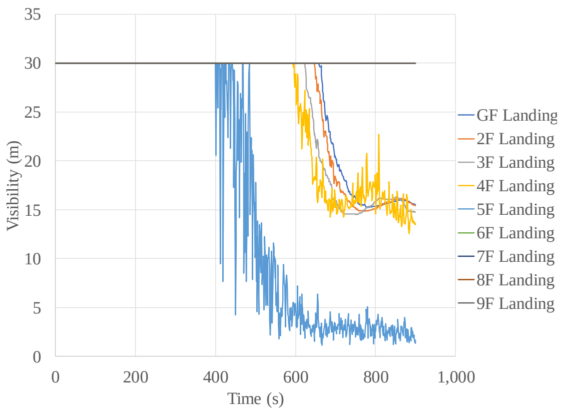

Figure 20: SD Case Landing Visibilities with 1 Relief Vent

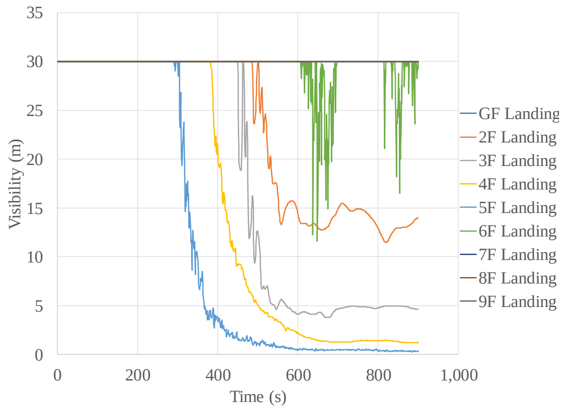

Figure 21: SD Case Landing Visibilities with 3 Relief Vents

It was observed that the pressurization system in the stairwell overcame the buoyancy of the smoke escaping the fire floor and pushed the flow downwards. Even though smoke flowed from the stairwell into the floor below, the visibility in the stairwell was still above the 10m limit as shown in Figure 20 for the case with only the relief vent activating on the fire floor. As the relief vent for the floor above and below the fire floor was not activated, the flow from the stairwell into that floor was limited to just the amount of air that could escape due to the wall leakage. This allowed more air to flow through the doors on the fire floor thus limiting the amount of smoke that would enter the stairwell.

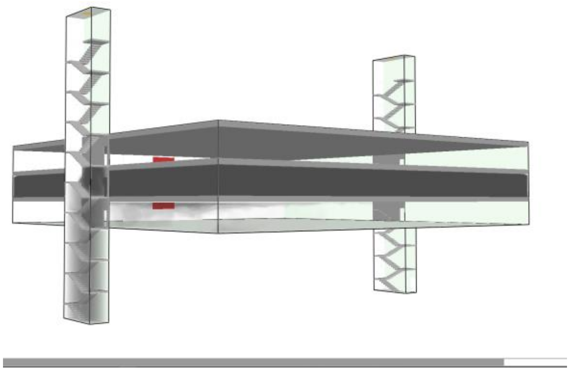

Figure 22: Snapshot of Smoke Flow in the Building with 1 Relief Vent Activating for SD Case

Looking at Figure 22 and Figure 23, if the relief vents for the fire floor and the floors immediately above and below were activated, it will compromise the visibility on the landings and the floor below. As the relief vents were activated, increased flows through the doors above the fire floor resulted in reduced flow of air into the fire floor thus allowing smoke to escape. This increased amount of smoke was then pushed into the floor below due to the downward flow of the stairwell pressurization system.

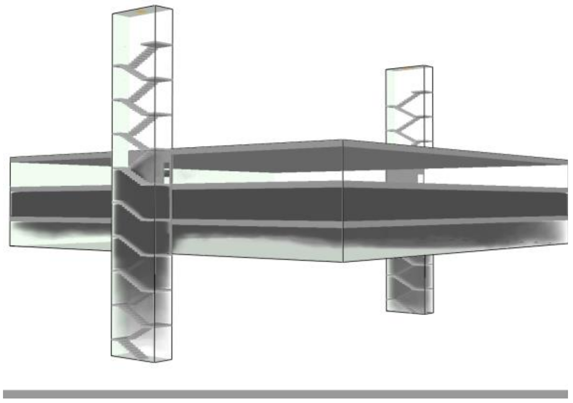

Figure 23: Snapshot of Smoke Flow in the Building with 3 Relief Vents Activating for SD Case

This was not the case for the sprinkler-controlled fire as shown in Figure 24. With 1 or 3 relief vents activating, the pressurization system was able to control the smoke from entering the stairwell and flowing into the floors below.

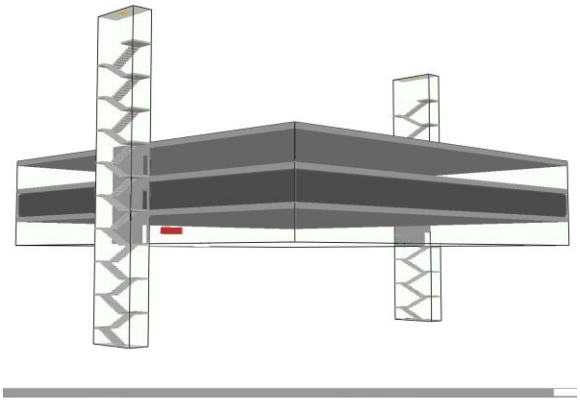

Figure 24: Snapshot of Smoke Flow in the Building for the SPK Case

4. ISSUES ENCOUNTERED

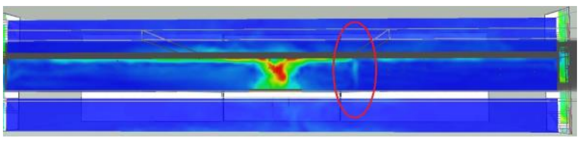

Figure 25: Location of Discontinuity

The first issue encountered was the lack of symmetry of smoke flow on the fire floor when the floor was divided into three meshes along the x-axis. There appeared to be a barrier even though there was a full height and length opening between the meshes of the room as shown in Figure 25.

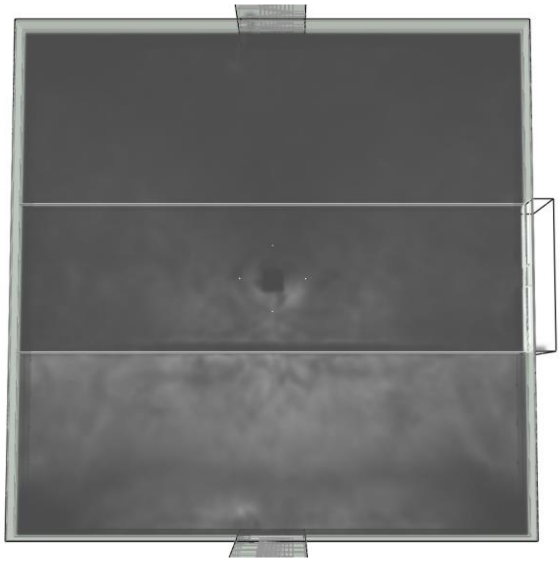

Figure 26: Location of Discontinuity (Top View)

Another view of the discontinuity can be seen in the uneven smoke filling of the room as shown in Figure 26. This barrier or discontinuity did not appear once the orientation was changed to divide the fire floor along the y-axis.

There was also uneven smoke flow into the stairs as observed in Figure 23. The front stair had more smoke filling than the rear stairs. This could be due to the pressurization system pushing air into the floor and affecting the smoke flow from the fire floor due to the uncontrolled smoke production. The relief vent had a certain area that would allow a maximum flow through so smoke had to escape from the fire floor from the stair entry doors.

Lastly smoke was flowing back into the sixth floor from the relief vents as shown in Figure 17. This was due to the relief vents being located vertically above each other.

5. CONCLUSION

A stairwell pressurization system design according to the design scenarios in AS/NZS 1668.1:2015 will only function as intended if phased evacuation is employed. Phased evacuation is only the fire floor and the floors immediately above and below the fire floor are evacuated first. All-out evacuation strategy will cause the pressurization system to not function as intended. The building must also be designed with relief venting on the floors. However, only the relief vent for the fire floor will be activated by the detection system on that floor. The relief vents must not be connected to each other such that activation of one vent activates all other vents. The stairwells also require a pressure relief vent as the flow rate required to achieve pressurization in the scenarios will generate pressures that may not allow the stair entry doors to open.

6. RECOMMENDATIONS

Errors occurred in the models when the fire floor was divided into three meshes along the Y-axis. This error combined with long run times per model and number of computers required to run the models meant that some scenarios could not be done. Future research should include the use of heat detectors. Devices should also be placed on the other floors to check if the floor has been compromised. The velocity planes and devices at the doors and relief vents should be changed to a mass flow or a volume flow. Location of the relief vents should be staggered to prevent the smoke from flowing back into the floor above. Another model should be done with the leakage area evenly split in the rear and front of the room as full height slots and as top and bottom leakage vents. Lastly, the incorporation of a working pressure relief vent in FDS can be looked at.

6.1. Acknowledgments

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