Analysis of Fire Smoke Spread and Evacuation Safety for the Elderly in Old Residential Communities: A Case Study of Shenyang Railway Community

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Abstract: Focusing on the widespread “internal-corridor” and “scissor staircase” layouts found in residential communities built in China during the 1970s–1990s, as well as the increasingly pronounced aging-related residential characteristics of these communities, this study used the fire dynamics simulation software PyroSim and the evacuation simulation software Pathfinder to construct full-scale models of typical old residential buildings. It specifically investigated how the open or closed status of doors and windows in the fire room facing the evacuation route—especially interior windows—affects smoke spread patterns. By comparing changes in temperature, visibility, and CO concentration under three typical scenarios (A, B, and C), the available safe egress time (ASET) for each scenario was determined. Taking into account the evacuation behavior of older adults, characterized by reduced mobility and longer response times, the required safe egress time (RSET) was calculated. The results show that opening the interior windows facing the corridor produces a “smoke short-circuit” effect, significantly shortening the time before hazardous conditions develop in public areas. Based on these findings, this paper proposes door and window control strategies and age-friendly retrofit recommendations for the evacuation of older adults in old residential communities.

Keywords: Residential Community; Evacuation of the Elderly; PyroSim; Pathfinder

1. Introduction

As China’s urbanization process shifts from incremental development to the quality improvement of the existing built stock, fire safety problems in aging residential communities built between the 1970s and 1990s have become increasingly prominent. Such buildings generally suffer from inherent deficiencies, including low fire-resistance ratings, inadequate fire protection facilities, and narrow evacuation routes. Meanwhile, China has entered a stage of deep population aging, and in some old residential communities the proportion of older residents has exceeded 40%, creating a compounded tension between a highly vulnerable population and limited fire safety capacity. In the field of fire dynamics, scholars in China and abroad have already carried out extensive research using numerical simulation techniques[1]. However, existing studies have mostly focused on newly built public buildings or standard residential buildings, while relatively little attention has been paid to the interactive effects among the three factors distinctive of old residential communities: multiple door-and-window operating conditions, coupling with natural ventilation, and the behavioral characteristics of older adults. In actual fires, in particular, infiltration caused by deteriorated doors and windows in old communities, together with residents’ mistaken practice of opening windows for smoke exhaust, often creates a “chimney effect” or “convective channel,” thereby accelerating the short-circuit spread of smoke[2]. Against this backdrop, this study takes the Shenyang Railway Residential Community as a prototype to construct a fire model for an aging residential unit[3]. PyroSim is used to simulate the movement of fire products under different door-and-window opening and closing conditions, and Pathfinder is employed in combination to model the evacuation process of a population with a high proportion of older adults under adverse conditions such as low visibility and restricted mobility. This study aims to quantify the impact of door and window states on safety margins and to propose performance-based compensatory measures from the perspective of age-friendly retrofitting, thereby providing theoretical support for disaster prevention and mitigation in urban renewal[4].

2. Models and Methods

2.1 Research Subjects and Building Model Development

This study focuses on representative aging multi-story residential buildings constructed in the 1980s and 1990s. Using a typical unit in a railway residential community in Shenyang as a reference, and drawing on survey data from similar old residential neighborhoods in cities such as Beijing, Changsha, and Harbin, a generalized building model was developed with the following characteristics: one staircase serving three households per floor, a scissor stairwell, a narrow vestibule, and single-glazed steel-framed windows. Such residential buildings, commonly built between the 1970s and 1990s, generally share several deficiencies: irrational floor-plan layouts, inadequate fire separation between dwelling units, narrow public egress routes that are often obstructed by stored belongings, and exterior windows—mostly single-glazed steel or wooden windows—that are prone to damage and have poor fire-resistance integrity[5]. Owing to the cramped interior space, limited corridor width, and poor ventilation conditions, smoke can rapidly accumulate in corridors and stairwells during a fire, severely impeding occupant evacuation.

2.2 Research Subjects and Building Model Development

This study simulated a fire scenario in which accumulated wooden clutter in the anteroom was ignited, with the maximum heat release rate (HRR) set at 1500 kW. Drawing on relevant studies of fires in older residential buildings, this type of scenario is typically characterized by a medium-growth fire; accordingly, the fire growth coefficient was taken as 0.0117 kW/s^2. Under these conditions, the time required to reach the peak HRR of 1500 kW is approximately 358 s, which is consistent with the 600 s simulation duration adopted in this study. This duration fully covers both the fire growth stage and the steady burning stage, thereby ensuring the engineering applicability of the simulation results. In addition, based on relevant findings on fire spread along building facades, the model also incorporates the pyrolysis and combustion characteristics of polyurethane insulation materials on the exterior walls of older residential buildings, so as to accurately reproduce the coupled influence of facade fire spread on the indoor smoke environment during a fire.

Measurement points for temperature, visibility, and carbon monoxide (CO) concentration were arranged in the link-corridor area. The measurement height was set at 1.6 m to correspond to the characteristic breathing height of adults and older adults. The numerical simulation duration was set to 600 s to ensure complete coverage of the main stages of occupant evacuation.

2.3 Design Operating Conditions for Doors and Windows

As shown in Table 1, this study established three typical fire scenarios, A, B, and C, based on the open/closed status of the doors and windows between the fire room and the connected evacuation route. These scenarios represent different natural ventilation and fire separation conditions, with the aim of comparatively analyzing the effect of window-opening ventilation behavior on smoke spread characteristics during a fire.

Table 1. Door and Window Condition Designe

Fire Scenario	Window 1	Door1	Door2	Heat Release Rate / kW
A	Closed	Open	Open	1500
B	Open	Closed	Closed	1500
C	Open	Open	Open	1500

2.4 Comprehensive Evaluation System

To scientifically assess evacuation safety, this study developed an ASET indicator system. This system comprehensively considers three critical thresholds of human tolerance when the hot smoke layer descends to 2.0 m above the floor or lower: visibility (critical threshold: 5 m), temperature (critical threshold for 30 min of continuous exposure: 60 °C), and smoke toxicity (critical CO concentration: 500 ppm).

3. Simulation Analysis of Fire Smoke under Multiple Operating Conditions

3.1 Analysis of Smoke Spread Characteristics

The smoke spread process under the three operating conditions exhibited significant differences. As shown in the comparative smoke spread diagram in Figure 1, under Condition A, because some windows remained closed, the supply of outside air was restricted, causing smoke to accumulate mainly in the local area of the antechamber and to advance slowly toward the stairwell. In contrast, under Condition B, all windows were fully open, establishing a stable convective pathway between the interior and exterior. After 50 s, the smoke rapidly propagated along the corridor and reached Antechamber 2 in only 113 s, making it the fastest-spreading case among the three conditions. The simulation contours in Figure 2 intuitively show that the opening and closing status of the windows played a decisive guiding role in the direction of smoke flow. Under Condition B, a distinct high-speed smoke transport pathway of "living room–antechamber–external window" was formed, a phenomenon that is highly consistent with the findings of studies on ventilation-driven smoke spread models.

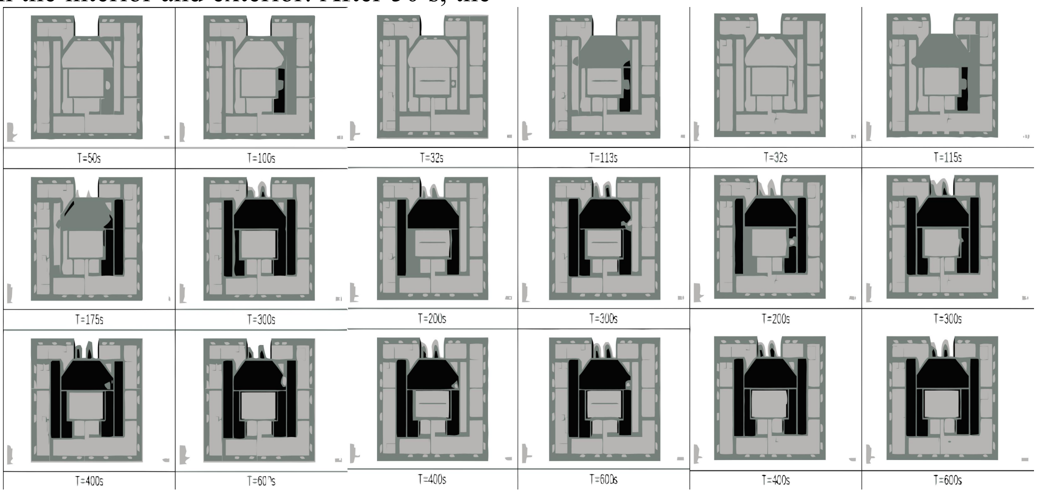

Figure 1. Comparison of Smoke Movement Maps

3.2 Temperature Field Distribution Analysis

As shown by the comparison of temperature distributions in Figure 3, the temporal evolution of the temperature field under each scenario is highly consistent with the previously described smoke arrival rates. In Case A, the temperature rises relatively gradually, and the anteroom still remains at a relatively low temperature at 175 s. In contrast, in Case B, owing to the rapid inflow of a large volume of hot smoke, the temperature in the anteroom at 175 s is already significantly higher than that in the other cases. When the simulation reaches 600 s, although the differences in the temperature fields among the three cases have narrowed somewhat, Figure 2 clearly shows that Case B consistently maintains the highest temperature level. Because the early formation of a high-temperature environment can markedly shorten the available safe egress time (ASET) of a building, the fully open-window ventilation mode is highly unfavorable for maintaining conditions conducive to safe evacuation[6].

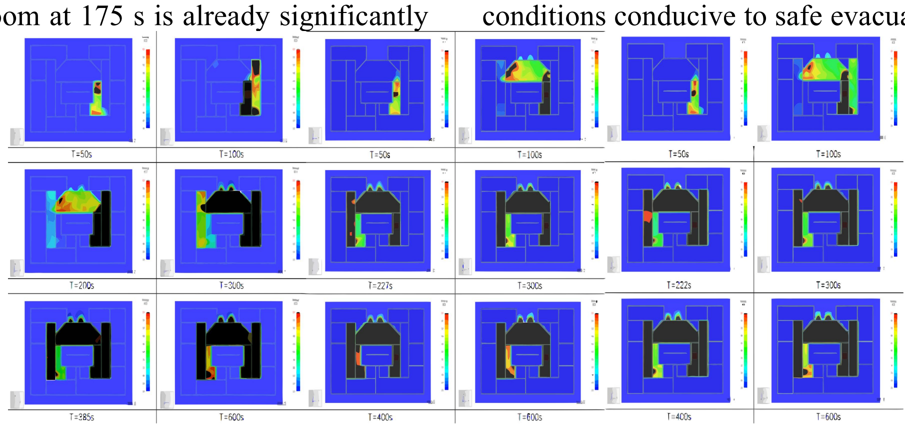

Figure 2. Comparison of Temperature Distribution Maps

3.3 Analysis of Visibility and Changes in CO Concentration

Visibility below 10 m is generally regarded as the critical condition for safe occupant evacuation. The comparative visibility simulation results in Figure 3 show that, under scenarios A, B, and C, the times at which the visibility in the anteroom dropped to the critical threshold of 10 m were 268 s, 200 s, and 222 s, respectively. The markedly earlier deterioration of visibility in scenario B is consistent with its strong convective characteristics and poses a severe threat to older adults, who rely heavily on visual cues. In addition, as shown by the comparison of CO concentration variations in Figure 4, under scenario A, restricted air exchange meant that the CO concentration in the anteroom did not begin to show a gradual accumulation trend until after 300 s. In contrast, under scenario B, intense natural convection drove a large volume of toxic smoke rapidly into the anteroom, causing the CO concentration in this area to rise sharply between 200 and 350 s and exceed the hazardous threshold of 500 ppm within a very short period.

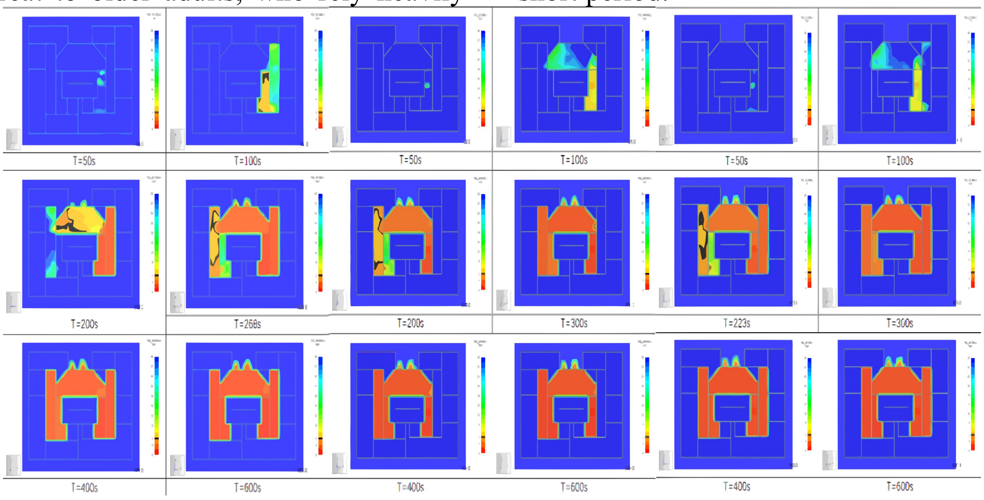

Figure 3. Comparison of Visibility Variation Maps

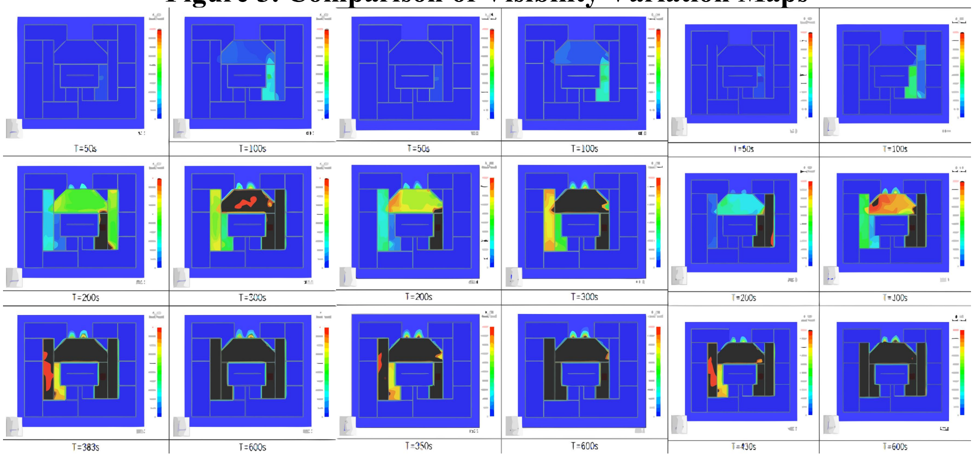

Figure 4. Comparison of CO Concentration Variation Maps

3.4 ASET Calculation and Comparison

This study integrated three indicators—temperature, visibility, and CO concentration—to determine the available safe egress time (ASET). The calculations and analysis presented in Table 2 show that Scenario B has the shortest ASET, at only 200 s. These results strongly confirm the pattern that the convective effect generated by opening exterior windows accelerates smoke intrusion into the anteroom, thereby significantly shortening the survivable time in residential building fires.

Table 2. Calculation and Analysis of ASET

Fire Scenario	Time When Temperature Exceeds the Limit / s	Time When Visibility Falls Below 5 m	CO Exceeds the Limit / s	Time of Hazard Onset / s Time
A	385s	268s	430s	268s
B	227s	200s	350s	200s
C	222s	223s	383s	222s

4. Evacuation Simulation and RSET Analysis for Older Adults

4.1 Analysis of Evacuation Behavior Mechanisms and the Characteristics of Older Adults

According to the SFPE and NFPA 92 standards, the fire evacuation process is generally divided into three stages: pre-movement, evacuation movement, and exit flow. In fire scenarios in older residential communities, older adults exhibit marked vulnerability at each of these stages. First, during the pre-movement stage, age-related declines in sensory abilities such as vision and hearing reduce older adults' sensitivity to fire smoke and unusual odors; in addition, they often need to locate assistive devices before taking action, which substantially prolongs their pre-movement time (typically reaching 60 – 120 s, far exceeding the 10 – 30 s observed among younger and middle-aged adults). Second, during the evacuation movement stage, older adults' mobility is significantly constrained: healthy older adults walk at only 0.5 – 0.7 m/s, while those requiring walking assistance may be as slow as 0.3 – 0.5 m/s, giving them an overall travel speed of only about 40% – 60% of that of younger and middle-aged adults[7]. Moreover, older residential communities commonly feature spatial constraints such as narrow stairways, dense doorways, and complex turns. When passing through such bottleneck points, older adults experience even greater speed reductions, with decreases of up to 50%. Finally, older adults are highly dependent on visual cues. When environmental visibility declines from 10 m to 5 m, the reduction in their evacuation speed (25% – 40%) is far greater than that of younger and middle-aged adults, indicating that deteriorating visibility has a pronounced amplifying effect on evacuation risk for the elderly.

4.2 Evacuation Simulation Setup and Path Utilization Analysis

The evacuation scenario constructed in Pathfinder in this study assumed that each household comprised 3 to 4 occupants, with a total of 10 to 12 people participating in the evacuation. All occupants followed the same evacuation route: "corridor walkway–anteroom 2–staircase–ground-level exit." Because the evacuation exit of "anteroom 1" was blocked by the fire source, all residents were forced to move in a single direction, thereby realistically reproducing the congestion conditions that are highly likely to occur in corridor fires in old residential communities[8].

Load and Utilization of Evacuation Routes:

1.During the initial stage of evacuation (0–18 s), occupants surged from each.

household doorway onto the corridor, causing brief and irregular congestion.

2.In the middle stage (18–36 s), the crowd began moving toward the vestibule, forming mixed single-file and double-file queues.

3.In the later stage (36–60 s), the last to leave were elderly individuals requiring walking assistance; their lower walking speed led to a longer tail of the queue.

4.3 RSET (Required Safe Egress Time) Calculation

In this study, tstart=54s

The following factors were considered: the average response time for older adults was taken as 30-60 s, while that for young and middle-aged adults was taken as 5-20 s; after comprehensive weighting, the resulting value was approximately 54 s.

If extreme scenarios are considered (e.g., older adults failing to notice the event or being asleep at night), this value may extend to 120-300 s, which will be discussed in the sensitivity analysis.

The simulation showed that the first person entered Vestibule 2 at 7 s, and the last person left Vestibule 2 and entered the staircase at 60 s. Taking into account crowding effects and behavioral variability, a safety factor of 1.5 was applied.

Therefore, tmovement=90s; the overall RSET was calculated as 144s.

This value is applicable to typical older residential communities under normal conditions and with a relatively small number of occupants.

4.4 Sensitivity Analysis of the Proportion of the Elderly Population

The trends in the evacuation simulation of older adults are shown in Table 3.

It can thus be seen that when the proportion of elderly occupants increases from 60% to 80%, the RSET rises by 30%; if the proportion reaches 100%, the RSET may approach or even exceed the ASET under certain scenarios.

Table 3. Evacuation Simulation Trend Table

Percentage of Elderly People	Average Speed (m/s)	Pre-movement Time (s)	RSET(s)
30%	0.85	35	~112
60% (Baseline)	0.55	54	~144
80%	0.43	78	~170
100% (Extreme)	0.38	120+	185~240

The evacuation safety assessment based on the ASET–RSET comparison is shown in Table 4.

Table 4. Evacuation Safety Assessment Table

Fire Scenario	ASET(s)	RSET(s)	Safety Margin
A	268	144	121 (Safe)
B	200	144	56 (Dangerous)
C	222	144	78 (Warning)

The conclusions are as follows:
1. Condition A is the safest: it has the largest safety margin, and smoke arrives the latest.
2. Condition C is acceptable: under a typical proportion of elderly occupants, it can still meet evacuation requirements.
3. Condition B is the most dangerous: it is highly likely to result in RSET approaching ASET, and may lead to evacuation failure, especially in real communities with a high proportion of elderly residents.

5. Comprehensive Safety Margin Assessment Based on ASET–RSET

5.1 Safety Margin Analysis and Risk Scoring

Drawing on NFPA and SFPE research, as well as domestic engineering experience, the safety margin (SM) is classified into four levels, as shown in Table 5:

Table 5. Safety Margin Classification Table

Safety Margin	Safety Level	Risk Description
SM ≥ 180 s	Grade I (Safe)	Slow fire development and stable evacuation conditions
120 ≤ SM < 180 s	Grade II (Relatively Safe)	Evacuation can be completed under normal circumstances
60 ≤ SM < 120 s	Grade III (Warning)	Slightly poorer conditions may lead to evacuation failure
SM < 60 s	Grade IV (Dangerous)	Casualties are highly likely

It should be particularly noted that, in real-world conditions in older residential communities, incidents such as elderly residents collapsing and clutter obstructing passageways can significantly reduce the safety margin; therefore, merely reaching Level III is already unsafe[9,10].

5.2 An Analysis of the Key Contradictions and Uncertainties in Fire Safety in Aging Residential Communities

Based on the above evaluation of safety margins, fire safety governance in old residential communities faces three core contradictions. First is the contradiction between "health needs and safety risks": residents' daily need for natural ventilation to improve indoor air quality can, in the event of a fire, readily turn into a risk of rapid smoke spread due to open doors and windows. Second is the contradiction between "evacuation needs and mobility capacity": rapidly spreading smoke continuously reduces the Available Safe Egress Time (ASET), while the slower mobility of elderly residents substantially prolongs the Required Safe Egress Time (RSET). Third is the contradiction between "structural constraints and code requirements": the inherent spatial deficiencies of older buildings, such as cramped vestibules and narrow staircases, make it difficult for conventional retrofitting to meet modern fire evacuation standards. Moreover, real fire scenarios involve many uncertainties[11]. Factors such as people being fast asleep at night, evacuation routes being obstructed by clutter, or older adults falling may all prolong the Required Safe Egress Time (RSET) by 30 to 200 seconds. Meanwhile, sudden factors such as external wind pressure and explosive battery fires involving electric bicycles may reduce the Available Safe Egress Time (ASET) by 20 to 120 seconds. The combined effect of these adverse factors can easily cause the safety margin to fall below the critical threshold, thereby resulting in severe casualties.

6. Improving the Smoke Control

Performance of the Anteroom and Stairwell

6.1 Architectural Design Optimization

Given that, in fires occurring in older residential communities, smoke can rapidly spread through doors, windows, and gaps, optimizing building smoke-control design is especially critical. It is recommended that automatic window-closing devices linked to smoke and heat detectors be widely installed on exterior windows in stairwells and their anterooms. When the ambient temperature exceeds 70°C or a high concentration of smoke is detected, these devices can be automatically triggered to cut off smoke convection pathways. In cold regions such as Shenyang, controllable smoke-proof windows that balance everyday natural ventilation with emergency smoke-blocking functions in the event of fire should be adopted, thereby avoiding dampness caused by long-term sealing. In addition, the airtightness of stairwell enclosure structures must be comprehensively improved. Measures such as replacing existing doors with Class B fire doors, adding high-temperature-resistant sealing strips, and sealing wall cracks can effectively reduce smoke infiltration. These retrofit measures are expected to extend the available safe egress time (ASET) by 60 to 120 seconds, thereby effectively ensuring the viability of stairwells as safe evacuation routes.

6.2 Age-Friendly Design of Evacuation Routes

Given the disadvantages older adults face during evacuation in low-visibility environments, age-friendly retrofitting of evacuation routes should focus on strengthening visual guidance and early warning. It is recommended that low-level lighting installed below 30 cm from the floor and reflective guidance strips be added along evacuation routes, and that continuous directional arrows be provided in smoke-proof vestibules and at stair corners, so as to ensure that the minimum horizontal illuminance at floor level under nighttime emergency lighting is no less than 15 lx. At the level of residential fire safety, in view of older adults'delayed perception of fire during nighttime sleep, the installation of high-sensitivity photoelectric smoke fire detectors and audible-visual alarm devices with a sound pressure level above 85 dB should be widely promoted (for individuals with hearing decline or reduced mobility, bedside vibrating alarm modules may also be added). These measures can effectively reduce evacuation pre-movement time by 60 to 120 seconds and constitute one of the core strategies for improving fire survival rates in this population.

6.3 Door and Window Opening Management Strategies

One-Touch Shutdown Control Strategy in the Early Stage of Fire

In view of the age-related physiological characteristics of older adults, particularly reduced mobility, it is recommended to introduce an in-home "one-touch fire emergency mode." Once activated, this mode would automatically close external windows and turn on evacuation lighting; meanwhile, it would interface with the community broadcasting system to deliver targeted voice prompts (e.g., "Please close the windows and evacuate by following the evacuation indicator lights"). In addition, building external windows should be equipped with damping devices to prevent mechanical rebound of the window sashes during the automatic closing process.

Time-Segmented Safe Ventilation Strategy

To reduce the risk of smoke spread caused by open windows during nighttime fires, it is recommended to implement a safety management policy of "ventilation during daytime hours (6:00–20:00) and keeping windows closed during nighttime sleep." At the same time, community residents' committees should be relied upon to regularly carry out public education on fire safety. This strategy can effectively reduce the probability of fire smoke entering indoor spaces at night, thereby extending the available safe egress time (ASET) by 20 to 50 seconds.

Community Fire Safety Training and Practical Drill Mechanism

For elderly residents, a normalized fire safety skills guidance mechanism should be established, with emphasis on hands-on instruction in exterior window-closing operations and low-posture evacuation techniques. It is recommended that evacuation drills be organized on a quarterly basis and that virtual reality (VR) technology be introduced to simulate fire and smoke conditions, so as to effectively enhance older adults'emergency response and risk-avoidance capabilities. In addition, illustrated and age-friendly fire emergency action cards should be developed to help elderly individuals accurately grasp key evacuation procedures.

6.4 Age-friendly Upgrading of Fire Protection Facilities

In response to the widespread absence or severe aging of fire protection facilities in older residential communities, and in light of the characteristics of this study, the following age-friendly upgrading measures for fire protection facilities are proposed:

(1) Install household smoke alarms and audible-visual alert devices. This measure is intended to address the primary hazard that older adults may have difficulty detecting a fire while asleep at night. It is recommended to install high-sensitivity photoelectric smoke alarms together with audible-visual alarms with a sound intensity of no less than 85 dB; for older adults with limited mobility, bedside vibrating alarm devices are also recommended. This measure can significantly reduce pre-evacuation time by 60–120 s and is among the most effective interventions for improving fire survival rates[12].

(2) Provide small household fire extinguishers and fire blankets. Considering the physical limitations and operational capacity of older adults, fire blankets are particularly suitable for extinguishing incipient kitchen fires and are the easiest firefighting tool for this group to use effectively in controlling a fire.

6.5 The Establishment of Community Governance and Fire Safety Management Systems

Establishing a "Community Fire Safety Steward" Mechanism

A "Community Fire Safety Steward" mechanism should be established with the joint participation of residents' committees, property management service providers, and fire safety volunteers, so as to create a coordinated community fire safety governance framework. Its main responsibilities include: regularly identifying safety hazards such as the unlawful stacking of sundries in hallways; inspecting the fire safety conditions of building components such as residents' doors and windows and exhaust ducts; urging residents to implement routine preventive measures such as closing windows at night; establishing a "key attention list" for vulnerable groups; and conducting regular home visits to elderly residents over the age of 80 in order to promptly assess their residential safety conditions and strengthen the community's capacity for fire risk prevention and control.

Regular fire safety awareness campaigns

These may take the following forms: notices on residential community bulletin boards; fire safety reminders in WeChat groups; educational videos played in public spaces; and door-to-door services to install alarms for elderly residents with limited mobility.

7. Future Research Directions

7.1 Main Research Conclusions

Based on coupled simulations using PyroSim and Pathfinder, this study systematically revealed the quantitative relationship between door and window opening conditions and evacuation safety for older adults in older residential communities. The results indicate that door and window conditions have a significant influence on smoke spread pathways and the evolution of the evacuation environment. In particular, the scenario in which both interior and exterior windows are fully open creates a pronounced "short-circuit effect," intensifying natural ventilation and convective flow, allowing smoke to enter and fill the anteroom more rapidly, and significantly reducing the Available Safe Egress Time (ASET). This suggests that, in the early stage of a fire, opening windows does not necessarily facilitate smoke exhaust; instead, it may become a major driver of rapid smoke spread.

Meanwhile, older adults generally exhibit longer response times, slower movement speeds, and greater sensitivity to low visibility and toxic smoke; as a result, their required safe egress time (RSET) is inherently longer, leaving only a very limited margin of evacuation safety in older residential communities. When further realistic uncertainties—such as nighttime sleep, objects piled in corridors, and delays in hazard recognition—are taken into account, the risk of failure of safe occupant evacuation under existing building conditions increases even further.

Based on the above findings, this study argues that improving fire safety in older residential communities cannot rely on any single measure alone, but should instead establish an integrated governance system that combines design, technology, and management. Specifically, installing automatic window-closing linkage devices that are activated under fire conditions can help suppress shortcut smoke spread; introducing age-friendly visual guidance and optimizing evacuation signage and lighting can improve older adults' recognition and movement efficiency; meanwhile, routine community fire inspections, corridor clearance, and emergency drills tailored to older residents can reduce uncertainty during evacuation. To a certain extent, these measures can extend ASET and shorten RSET, thereby significantly enhancing the overall fire resilience of older residential communities and the level of protection for occupants' life safety.

7.2 The Novelty and Contributions of this Study

(1)A comprehensive evaluation model was developed to encompass the "building characteristics of old residential communities–multiple door and window configurations–evacuation behavior of older adults," overcoming the limitations of existing studies that are restricted to single-scenario analyses, overlook behavioral differences among the elderly, and give insufficient consideration to constraints imposed by the community environment.

(2) For the first time, the mechanisms by which door and window opening conditions influence the "short-circuit effect" of fire smoke, as well as the corresponding patterns of variation, were quantitatively revealed. The study shows that, in the early stage of a fire, exterior windows generally cannot effectively serve as smoke exhaust openings; instead, they may become "accelerated pathways" that promote the rapid spread of smoke, with the risk being most pronounced when the exterior windows are fully open. These findings provide an important scientific basis for optimizing smoke prevention and exhaust design in community buildings, the management of doors and windows, and fire emergency evacuation strategies.

(3)An ASET-RSET safety margin evaluation framework applicable to aging residential buildings has been established, providing direct support for assessing the effectiveness of fire protection retrofits in older residential communities, verifying performance-based fire protection designs, and determining fire risk levels.

7.3 Limitations of the Study

(1) Fire simulation is constrained by idealized conditions. The furniture layouts assumed in the study are relatively simplistic, and special fire scenarios such as electric vehicle battery deflagration are not covered. Moreover, the simulations cannot fully reproduce the real dynamic changes in environmental factors such as wind direction and air temperature.

(2) Evacuation models fail to adequately capture the complex behavioral characteristics of older adults. They do not yet comprehensively incorporate special behaviors such as panic, diminished spatial orientation, returning to retrieve belongings, and mutually assisting one another, nor do they fully reflect the pronounced interindividual differences in health status. In real-world scenarios, these factors may substantially increase the required safe egress time (RSET).

(3) The construction costs and practical feasibility of age-friendly retrofit measures still require further verification. Given the significant differences among regions and building types in terms of retrofit costs, construction conditions, and implementation difficulty, future research should combine field investigations with case data to conduct more targeted analyses, thereby providing more robust and detailed empirical support for the relevant conclusions.

Acknowledgments

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