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CFD-Based Validation Study on the Fire Prevention Wisdom of Ancient Village Houses in Western Hunan

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Abstract: Ancient villages are precious architectural treasures that have been protected from fire hazards for centuries through traditional fire prevention strategies. However, research on traditional fire response strategies is limited, with existing studies mainly focusing on climate response strategies, conservation, and renewal. No prior research has revealed the quantitative fire response strategies used for ancient buildings. This paper takes the first ancient village in western Hunan, High-Chair village, as an example, and it (1) assesses the fire risk of High-Chair village; (2) determines the traditional fire response strategies of the ancient village, including fire prevention culture, residential layout, wall forms, and fire resistant materials; and (3) uses CFD simulation to reveal and verify the science and rationale of the traditional patio layout and hill wall forms. The study suggests utilizing CFD simulation to quantitatively assess and validate fire response strategies. Such knowledge of fire prevention can provide fire mitigation solutions for rural construction.

Keywords: traditional wisdom; fire mitigation; CFD; risk management; ancient village

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1. Introduction

1.1. Background

Since ancient times, fire has been the ultimate threat to human safety and historical buildings. Ancient people gave importance to building fire prevention since the construction of buildings, and the issue of building fire prevention has a long construction history. The ancient villages in Western Hunan are the largest legacy of the Chinese farming civilization [1,2], rich in historical information and cultural landscapes [3,4]; some were even built over 1000 years ago. After thousands of years of coping with various disasters and natural and cultural environments, ancient village dwellings developed a series of fire response strategies and methods that are highly ethnic. These effective strategies have preserved the villages' heritage and positively impacted various past and future disasters. It is critical to disseminate this traditional fire prevention knowledge. Our responsibility is to learn from our ancestors' fire prevention knowledge and combine it with other modern techniques to form effective disaster mitigation measures suitable for sustainable development in modern villages.

This study was conducted in the context of Western Hunan in China. Traditional Chinese villages are called ancient villages. The western Hunan region is one of the principal gathering areas of traditional Chinese villages, preserving several villages [5]. There are 265 villages selected for the fifth batch of traditional villages in China, with 66% of them in Hunan Province [6,7]. These ancient villages also represent the typical characteristics of Western Hunan in terms of location, planning, and other aspects of the region, ethnicity, and specific historical periods. However, the farming cultural heritage located in remote mountainous areas is strongly impacted by modern civilization, influenced by excessive commercial development and misinterpreted by new rural construction [8]. During the historical process, spontaneously formed fire and disaster prevention systems in ancient villages have been severely damaged or destroyed, while traditional fire strategies that have withstood long disasters have been preserved and combined with modern technology to produce more effective fire measures. This ancient ancestral wisdom is also important to the local ethnic culture, and it is our responsibility to record it, interpret it, and pass it down to future generations.

1.2. State-of-the-Art: Fire Response Strategies for Ancient Buildings

Several research results were obtained regarding different survival knowledge used in ancient buildings. Compared to response strategies for natural hazards such as climate [9], floods [10], wind hazards [11,12], and earthquakes [13,14] in ancient buildings, conventional fire prevention strategies have been ignored in the field of ancient building conservation research. Joseph Needham [15] investigated the unique feng shui culture of traditional Chinese villages and their traditional passive disaster prevention concepts. Chip Sullivan [16] explained the traditional ecological disaster prevention strategies of ancient architects and gardeners by studying classical gardens in various countries. Li Hequn et al. [17] summarized the disaster prevention measures in ancient buildings, including fire escapes, water sources, and technology and its management. Zheng Yihong [18] examined the fire prevention strategy in ancient buildings using Huizhou ancient buildings as an example, based on five elements of culture. Scientific fire prevention strategies in ancient buildings have been widely recognized and researched. However, existing research is primarily summarized and qualitatively explained from an ecological and natural standpoint via field research, etc., and lacks quantitative scientific validation and revelation [19].

1.3. State-of-the-Art: Fire Studies on Ancient Buildings

The philosophy of construction in harmony with heaven and mankind has always guided Chinese architecture, instructing residents to build homes with local materials and according to their local terrain [20]. This is a climate-responsive strategy for ecological design [21–25] that considers potential hazards, including fire in the case of wood. Wood is the most commonly used building material in Chinese architecture, and the heavy use of wood resulted in a large fire load on ancient structures. Through-drawer structures with good ventilation also contributed to the extent of fire spread [26]. Currently, the main focus is on the assessment of fire risk and the application of modern fire prevention techniques and proposed fire rescue measures (Table 1) involving historical towns [27–29], single dwellings, heritage temples [30,31], bridges [32,33], and villages [34–36]. This is the first quantitative study of traditional fire prevention strategies in ancient dwellings. Compared to timely rescue after a fire, it is more effective to reveal traditional fire strategies and use them for rural development, reducing the chances of fire.

Table 1. Overview of fire-related studies focusing on ancient buildings.

Reference	Year	Location	Type(s)	Method	Results
Yufei Wang et al. [37]	2022	Shanxi Province, China	Heritage buildings	Testing	Determining the burning behavior of ancient wood and its differences from modern wood
Fupeng Zhang et al. [34]	2022	Western Hunan	Ancient buildings	CFD	Revealing "survival design strategies" for village sites, layouts, and street patterns

Table 1. *Cont.*

Reference	Year	Location	Type(s)	Method	Results
Guanjie Hou et al. [38]	2021	Southwest China	Ancient town	Multi-objective genetic algorithm	Proposed an innovative procedure for determining the optimal fire station location
Julio Tozo Netoa and Tiago Miguel Ferreira [39]	2020	Ponta Delgada	Ancient buildings	GIS Tools	Analyzed the cost of strategies to mitigate fire risk in historical centers
Biao Zhou et al. [40]	2012	Tianjin, China	Yuan Residence	CFD	Proposed fire risk assessment and control methods
Chunyan Yuan et al. [41]	2018	Shanxi Province, China	Dangjia Village	Site investigations	Investigated fire hazards in heritage villages and provided fire safety assessments
Jiang, ShaoFei et al. [42]	2020	China	Ancient buildings	In-situ test	Developed a structural health monitoring system based on FBG sensing
Zhang Xiaojin et al. [43]	2022	Xijiang, China	ancient buildings	Gustav method	Proposed fire risk assessment model for large wooden structure ancient buildings
Fupeng Zhang et al. [44]	2022	Western Hunan	ancient buildings	CFD	Proposed a CFD-based framework to assess fire risk in wood-frame villages

1.4. Fire Research Methods for Ancient Buildings

Field studies are the traditional method for assessing fire risk in ancient buildings. CFD (Computational Fluid Dynamics) software is also widely used to visualize and analyze building fire conditions (temperature, CO concentration, and visibility) [30,45–48]. Xu Lei et al. [49] conducted a numerical simulation study based on CFD software on the effectiveness of water sprays in kitchen fires in ancient buildings. Using CFD software, A. Manuello Bertetto et al. [50] calculated the spread of fire and smoke on the roof of Notre Dame de Paris Cathedral. Weinschenk, Craig G. et al. [51] explained an attic fire incident in a wood frame residential structure in Chicago, Illinois, using CFD software. Wang Xiaoyu et al. [52] analyzed the flame spread behavior of fire-retardant wood in ancient Fuling buildings using CFD software. Therefore, this study used CFD software to simulate fire combustion conditions in ancient village dwellings.

1.5. Purpose of the Current Study

The purpose of this paper is to (1) summarize traditional fire prevention strategies in the ancient High-Chair village through field research, (2) analyze the effectiveness of different fire prevention strategies through quantitative visualization of CFD simulations, (3) reveal and verify the scientific nature of traditional fire prevention strategies in the ancient High-Chair village. The geometry, courtyard layout, and building size of ancient houses in Western Hunan are similar to those found in other parts of China, Korea, and Japan. This study's validation framework and methodology were also applied to ancient dwellings in other regions.

2. Methodology

2.1. Research Object

Xiangxi region is bordered by Hubei Province to its north and Chongqing city and Guizhou province to its west, and is located in the northeastern part of the Yunnan-Guizhou Plateau [53]. The representative ancient village of Xiangxi region, High-Chair village, became the object of the study (Figure 1). It is one of the largest and best-preserved ancient folk architecture villages of the Ming and Qing dynastic periods found so far in Hunan Province. It is one of the top ten ancient villages in China and a key national cultural relic protection unit. According to Feng Shui culture, the village site of High-Chair village is ideal and suitable. This village also preserves 104 ancient dwellings built between 1380 and 1881. Its population is 2206 people, and its total construction area is 19,416 square meters [34].

(a) (b) (c) (d)

Figure 1. (**a**) Location of High-Chair village in China; (**b**) current condition of the residential dwellings in High-Chair village; (**c**) situation of residential clusters; (**d**) roof and building material conditions.

The study consisted of three phases: fire risk assessment, traditional fire prevention strategy investigation, and the use of CFD simulation to validate the fire risk in the residences in High-Chair village. Figure 2 shows the roadmap of the three phases of the study.

The following are the current study's innovations. To begin, the study proposes a method for visualizing and quantitatively validating the fire prevention strategies of ancient village dwellings using CFD simulation. Second, it examines ancient village dwellings' fire prevention strategies and lays the groundwork for future research on combining these traditional measures with modern technologies. These traditional disaster prevention methods may not prevent all modern disasters, but when combined with modern technology, they may facilitate effective mitigation measures. This provides a reference for village construction in the western Hunan region and elsewhere.

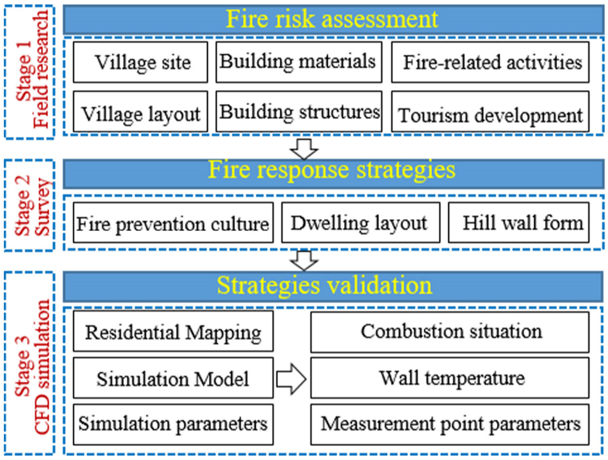

Figure 2. Three main research phases.

2.2. Field Research

2.2.1. Fire Risk

Western Hunan is a geographical environment dominated by mountains, hills, and plains that rise higher in the northwest and lower in the southeast. Besides Han Chinese, western Hunan is also inhabited by the Tujia, Miao, Dong, Yao, and other ethnic minorities [54]. The total population of these minority inhabitants accounts for 95% of the ethnic minorities in Hunan [55] Province. The unique natural and human environments have shaped unique ancient villages in Western Hunan. This study investigated the fire risks in these ancient villages and included the following six aspects:

- Village site selection

Ancient villages in Western Hunan are often located in remote mountainous areas, far from the firefighting units in towns (Figure 3a). For example, Dajing, Pingtan, and Qixi villages are more than 20 km away from the nearest fire rescue unit, and their waiting time for these units is more than thirty minutes [44]. These mountainous areas are also rich in forest vegetation resources, which can quickly spread a fire.

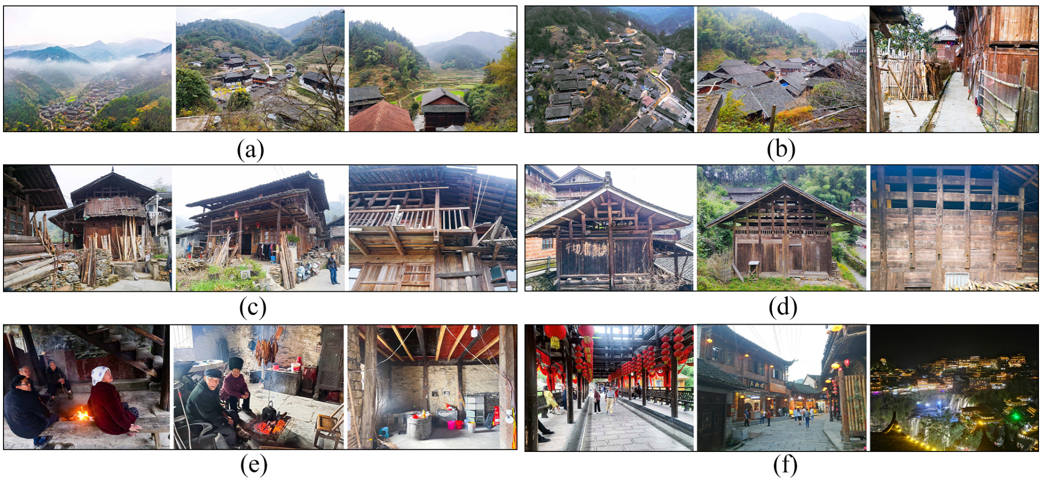

Figure 3. (**a**) Village site selection in Xiangxi area; (**b**) village layout; (**c**) building materials; (**d**) building structures; (**e**) fire-related activities; (**f**) fire risk from tourism development.

- Village layout

The layout of ancient villages in Western Hunan follows the mountainous terrain, forming a narrow and winding street pattern (Figure 3b). The winding streets and alleys are unconducive for crowd evacuation and firefighting operations. The lack of sufficient flat land to construct dwellings has even formed continuous clusters of buildings. When a fire occurs, it is likely to result in a large-scale residential fire accident if it is not extinguished in a timely manner.

- Building materials and structures

In Xiangxi's ancient villages, wood is the primary building material (Figure 3c,d). Wood's moisture content has an effect on its combustion performance [56]. A building's fire load is critical for determining fire scale and danger level [57]. Therefore, a Biaozhi high-precision wood moisture tester was used to measure the moisture content of wood in High-Chair village at 36 locations, including columns, walls, beams, window frames, and stairs. The fire load of 23 residential houses in High-Chair village was also surveyed and estimated based on the Technical Code for Fire Protection of Building Steel Structures. The density of common fir wood was 440 kg/m^3, and the calorific value of wood combustion was 18.4 MJ/kg [44]. Due to the variability in active loads caused by objects such as household goods and indoor furniture in different dwellings, the goal of this calculation was fixed fire loads, such as dwelling structural members.

- Fire-related activities

The number of fires caused by electrical fires and careless fire use exceeds half of all fires in rural Hunan [44]. There are several fire-related activities in Western Hunan (Figure 3e) with unique ethnic origins and habits. Along with worshiping the gods in ancestral halls, temples, and wind and rain bridges [32] and worshiping ancestors indoors, fire pits are essential in fire rooms for smoking bacon, family gatherings, receiving guests, discussions, and rituals. In addition, solid fuels such as coal and wood are widely used for cooking and heating [58]. The energy patterns and fire habits of the High-Chair village were investigated, which helped to assess the fire risk.

- The fire risk of tourism development

The ancient villages of Western Hunan are being developed for tourism (Figure 3f) due to their unique ethnic culture and architectural forms [8,59]. Tourism development has, in turn, developed the local economy. However, some tourists litter cigarette butts while children play with fire. The prevalence of tourists during the peak tourist season make residential fire prevention more difficult. Many commercial appliances and disorganized segments of directly exposed electrical wiring are potential fire hazards.

2.2.2. Residential Fire Wisdom

Fire control strategies in ancient villages have evolved over thousands of years, as has the construction history, creating a series of local fire prevention strategies. Four aspects of traditional fire prevention strategies in High-Chair village were investigated and analyzed, including fire prevention culture, residential layout, wall forms, and fire prevention materials.

- Fire prevention culture

Before technology, traditional fire prevention culture had subjective and spiritual aspects. Before discovering effective technical fire prevention measures, our forefathers aspired to and spiritually pursued traditional fire prevention culture. It reminds residents to deal with a focus on fire danger, to be on the lookout for fire hazards, and to learn about technical fire prevention measures. The fire prevention culture of ancient villages is reflected in the unique decorative and component forms of the dwellings, which are integral to ancient dwellings.

The fire prevention culture of High-Chair village mainly includes two aspects (Figure 4). One is the folklore stories of animals, deities, and ornaments that can extinguish fires and prevent disasters, such as scops, lion head patterns for door locks, Shi Gandang (God), fire-avoiding pearls, and eight diagram mirrors. Second, people believe that the color black reduces the risk of fire. Black represents water in the five elements of culture and can restrain fire, and is used in black tiles and the text of water-related plaques.

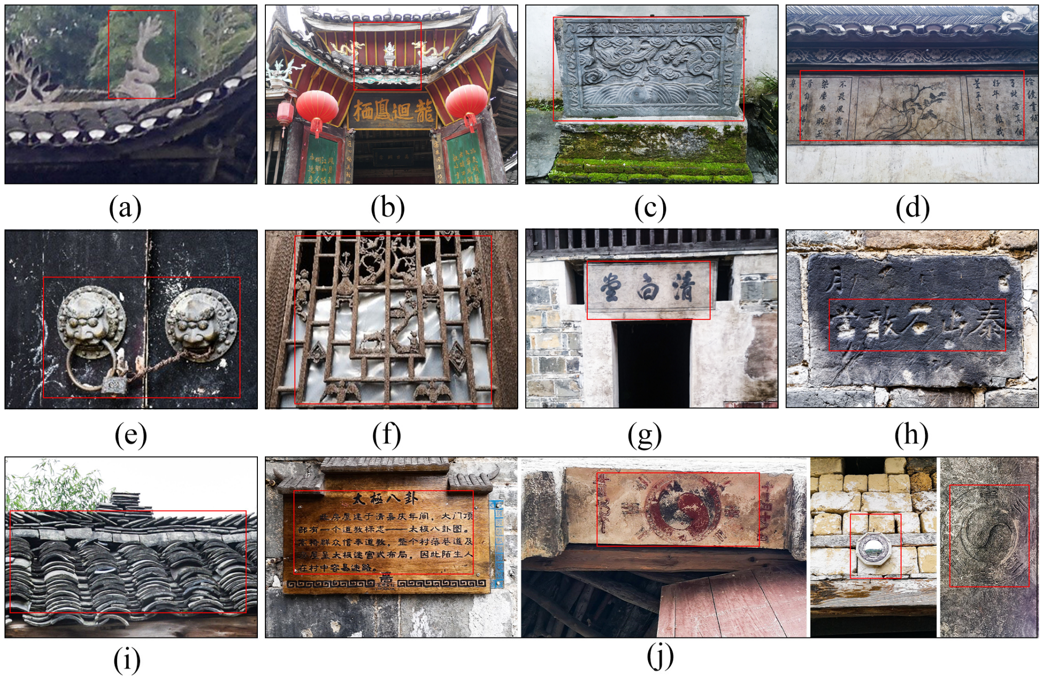

Figure 4. Fire prevention culture in High-Chair village: (**a**) ornament on the roof ridge in the shape of a legendary animal; (**b**) pearls to extinguish fires; (**c**) water storage tank; (**d**) mural; (**e**) door lock; (**f**) engraved window frames; (**g**) plaque; (**h**) Shi Gandang (God); (**i**) black tiles; (**j**) eight diagrams.

- Dwelling layout

Dwellings in High-Chair village are called Jiaozi Houses or Yinzi Houses, which are kinds of dwellings with a courtyard and fence. A Jiaozi House means defense and storage. Depending on the layout of rooms and patio, Jiaozi Houses can be divided into three types: the 目-shaped plan, the 回-shaped plan, and the 日-shaped plan (Figure 5 and Table A1). The patio facilitates indoor ventilation and lighting and is also a semi-public place for residents to communicate with each other in their daily lives and activities [60]. In terms of fire prevention, the patio separates the house from the courtyard wall, creating effective spatial fire separation. To investigate the role of patio fire protection, the patio dimensions of 40 typical Jiaozi houses were measured and compared to the street dimensions and the fire safety spacing between residential houses. The fire protection effects of various patio types were also simulated, as detailed in Section 2.3.

- Hill wall form

The form of a hill wall, i.e., a fire-sealing hill wall, is a crucial fire prevention measure for villagers' residences in High-Chair. The orderly and zigzag variation parts of the hill wall beyond the roof also form a distinctive architectural form. It is higher than the ridge of the roof so that the two adjacent houses remain separated. Outer parapet walls in High-Chair village are constructed of brick, and interior partition walls and columns are of wood frame construction. Brick and stone masonry walls have decent fire resistance with a fire resistance duration of over 6 h. The fire-sealing hill wall is 300–400 mm thick, larger than the traditional brick wall of 240 mm, and has decent structural stability during fires.

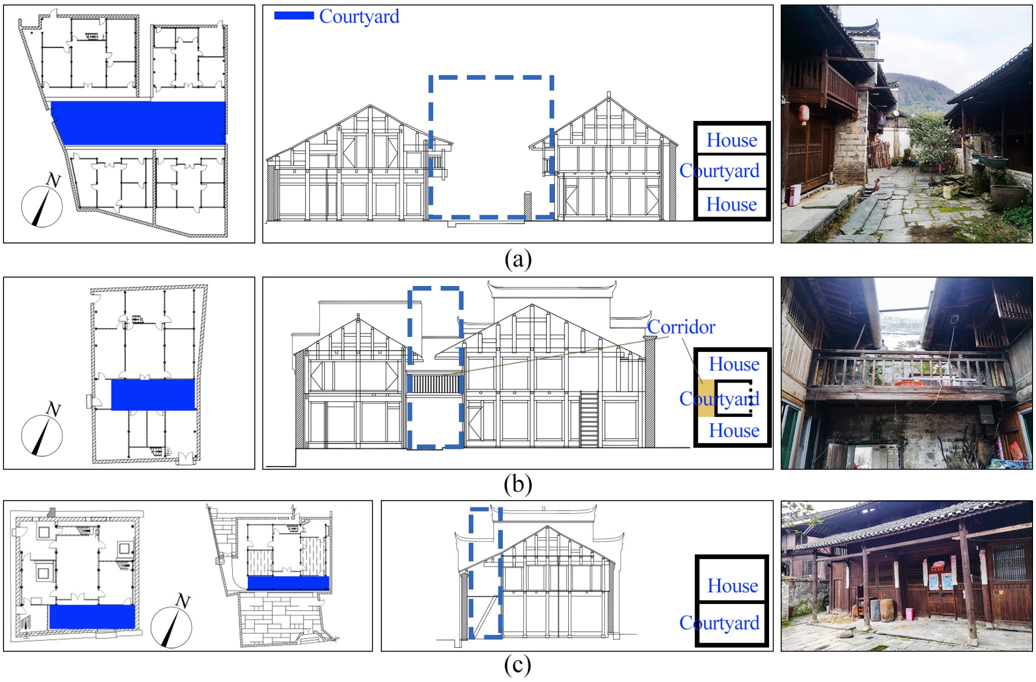

Figure 5. Three types of dwellings based on the form of the patio: (**a**) the 目-shaped plan; (**b**) the 回-shaped plan; (**c**) and the 日-shaped plan.

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In addition to fire-sealing walls, other types of hill wall surfaces can be found in High-Chair village. Based on the relationship between the wall and the roof, they can be divided into four scenarios: Scenario 1 is a sealed firewall (Figure 6a); Scenario 2 is a sealed household wall whose height is the same as that of the roof and where the rafters are not exposed outside the wall (Figure 6b); Scenario 3 is a hill wall whose height is the same as the roof and where the rafters are exposed outside the wall (Figure 6c); Scenario 4 is a wooden hill wall (Figure 6d). The fire effects of the various types of walls were simulated as detailed in Section 2.3.2.

2.3. Software Simulations

2.3.1. Impact of Patios on Fires

Pyrosim software helped model the fire situation of residential houses in High-Chair ancient village and the Yang Fangxiu house to study the effects of different patios on the fire performance in these houses. Three scenarios were included in the requirements that were chosen. The first scenario is a typical Jiaozi house as an independent building fire protection unit, thereby excluding the influence of external fire factors in residential houses on simulation results. In the second scenario, there are houses on both sides of the courtyard. In the third scenario, the dwellings were kept intact and used.

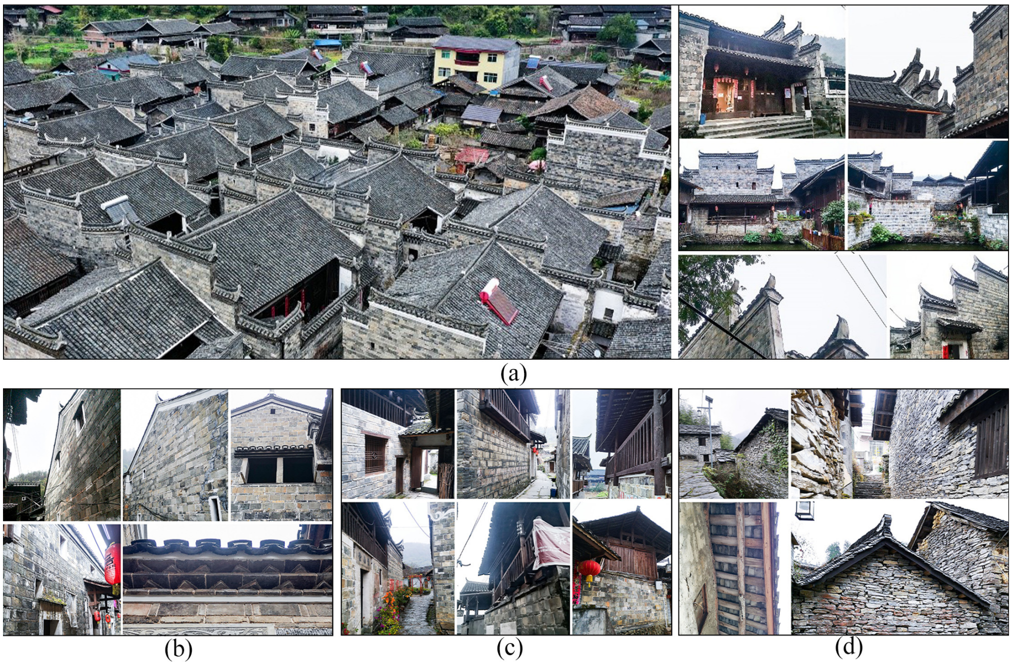


Figure 6. Four types of residential houses according to hill wall form: (**a**) fire-sealing hill wall; (**b**) fire-sealing household wall; (**c**) rafters sticking out of the hill wall; (**d**) wooden hill wall.

- Simulation Model

First, based on the actual measurement results, a model of the Yang house was created using SketchUp software; then, the DXF model output from the software was loaded into Pyrosim software. Finally, the burning situation was simulated by setting parameters on Pyrosim [32,44] (Figure 7). There was some variability between active loads, due to objects such as furniture and household items, in different homes; thus, the target of this calculation was mainly fixed fire loads, such as structural members.

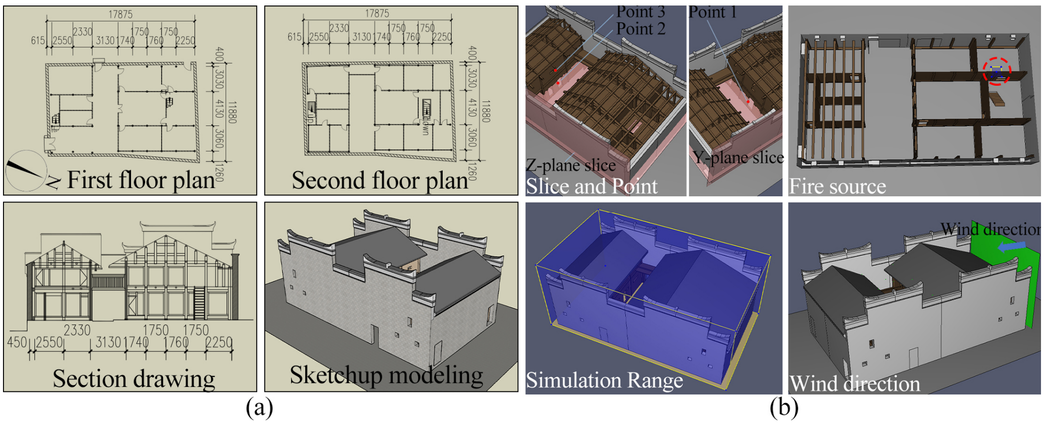
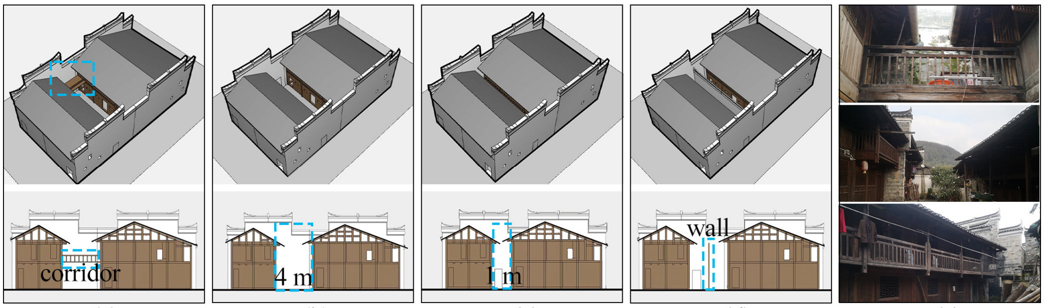


Figure 7. (**a**) Measured dimensions of the Yang Fangxiu house; (**b**) Simulation model created based on actual dimensions.

Four scenarios were designed to investigate the effect of the patio on fire performance in the dwelling. In all scenarios, the dwellings are modeled based on real measurements and are kept the same. Patio size and type are the variables. Based on the findings in Section 2.2.2 regarding the size and average depth of the patio, a depth of 4 m was chosen for scenarios 1, 2, and 4. Table 2 and Figure 8 show the specific parameters and models.

Table 2. The specific parameters of four scenarios.

Scenario	Patio Form	Patio Depth	Patio Width	Patio Partition
1	homocentric squares	4	10	Patio
2	shaped like 目	4	10	Patio
3	shaped like 目	1	10	Patio
4	shaped like 目	4	10	Wall



(a) (b) (c) (d) (e)

Figure 8. Four types of patio forms in residential models: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4; (**e**) actual patio conditions.

- Simulation parameters

The fire source, simulation grid, slices, measurement points, material parameters, wind speed, wind direction, ambient temperature, and simulation time were set.

Fire source: The maximum heat release rate of the ignition source is 1 MW, based on Chow, C.L. and Chow, W.K. [61] and Kim, H.J. and Lilley, D.G. [62]. The ignition source is controlled with time to reach a maximum after a period of time and declines to extinction thereafter. The model considers that the fire occurs indoors, and the interior building materials are flammable except for the courtyard wall. The fire source is the indoor fire pit area of the Yang Fangxiu residence. A Large Eddy Simulation (LES) [63] was used.

1. The simulation grid was set up according to the grid division method recommended by the software user manual, and the simulation was consistent with the grid independence test experiment.
2. A Z-plane slice was placed at the normal height of the human eye, 1.6 m above the ground, on the first floor of the house. On the face of the hill wall, a Y-plane slice was placed.
3. Three monitoring points were set up, one at a distance of 0.5 m from the first-floor room of the fire source residence and a height of 1.6 m, and two on the other side of the patio at a distance of 0.5 m from the room and heights of 1.6 m and 4.6 m, to simulate changes in smoke temperature, visibility, and CO concentration for three fires.
4. The wind speed is the annual average wind speed in High-Chair village. To consider the most dangerous situation, the wind direction is the same as the direction of the residential arrangement.
5. Based on relevant studies and historical weather data in Western Hunan, the ambient temperature was set to 17 °C [64].
6. The simulation time is 1800 s.

The specific parameter settings are shown in Figure 7b, Tables 3 and 4.

Table 3. Specific parameter settings for the four types of patio scenarios.

Scenario	Fire Source	Grid Size	Fire Size	Grid Number	Ambient Temperature	Wind Direction	Wind Speed	Time
1	1 MW	$0.2 \times 0.2 \times 0.2$ m	1 m $\times$ 1 m	78,039	17 °C	North	1.5 m/s	1800 s
2	1 MW	$0.2 \times 0.2 \times 0.2$ m	1 m $\times$ 1 m	78,039	17 °C	North	1.5 m/s	1800 s
3	1 MW	$0.2 \times 0.2 \times 0.2$ m	1 m $\times$ 1 m	70,122	17 °C	North	1.5 m/s	1800 s
4	1 MW	$0.2 \times 0.2 \times 0.2$ m	1 m $\times$ 1 m	78,039	17 °C	North	1.5 m/s	1800 s

Table 4. Parameters of the materials recommended for fire control.

Material	Density kg/m^3	Specific Heat Capacity kJ/(kg·K)	Thermal Conductivity W/(m·K)
Fire wood	500	2.52	0.108
Small green tile	2800	0.92	0.76
Stone	2800	0.92	3.49
Brick	1700	1.05	0.75 (100)

2.3.2. Impact of Hill Wall Form on Fires

- Simulation Model

Fire simulations were conducted for residential houses with different hill wall forms to study their influence on the fire performance of residential houses in the ancient High-Chair village. The first house in the ancient village and the Yang Yungui house were selected for case study. The Yang Yungui house is a Qing Dynasty wooden structure, which is a typical wooden residence in High-Chair village (Figure 9a), and the first house in the ancient village is an existing Ming Dynasty Jiaozi house in High-Chair village, which is well-preserved and still used today (Figure 9b). The model-building method was the same as in Section 2.3.1 (Figure 9c).

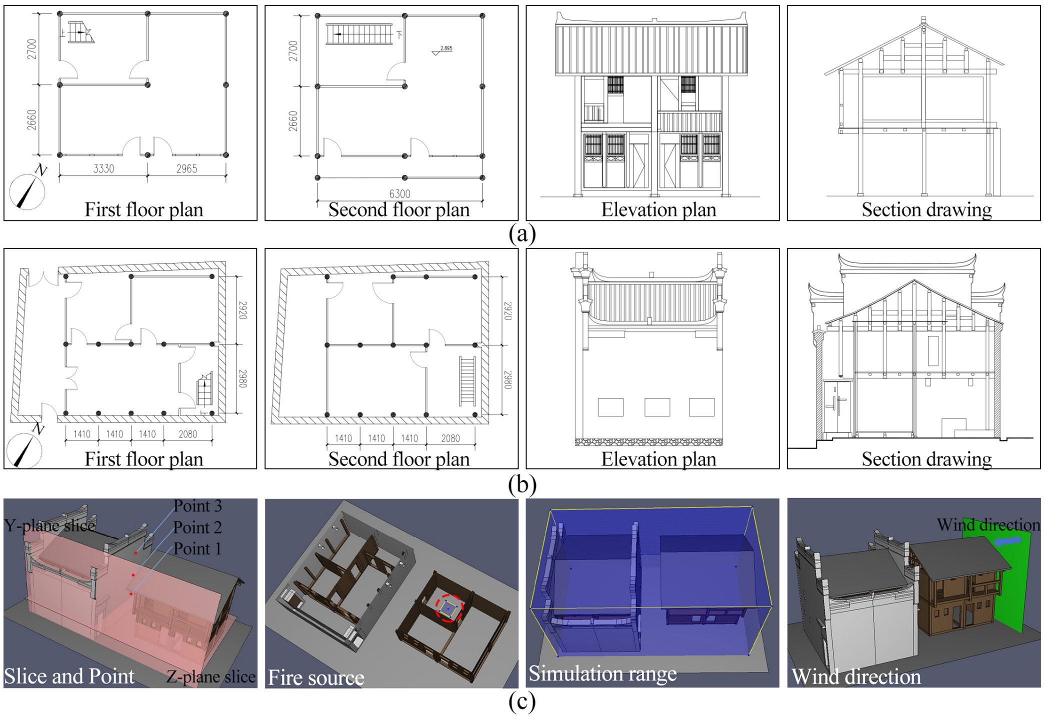


Figure 9. (**a**) Measured dimensions of the Yang Yungui House; (**b**) measured dimensions of the first house; (**c**) simulation model created based on actual dimensions.

Four scenarios were created to investigate the impact of hill wall shape on the fire performance of residential houses (Figure 10). The Yang Yungui house remained unchanged throughout the scenarios, and four different types of dwellings were created by changing the wall form of the first house in the ancient village. The plan dimensions of all models were created based on real measurement data.

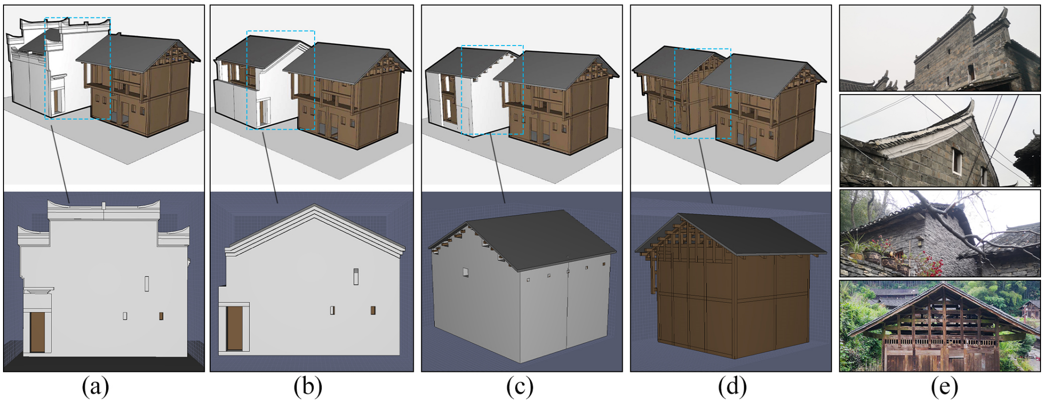


Figure 10. (**a**) Simulation model of fire sealing hill wall; (**b**) simulation model of fire sealing household wall; (**c**) simulation model of rafters sticking out of the hill wall; (**d**) simulation model of wooden hill wall; (**e**) hill wall actual condition.

- Simulation parameters

The firewall had good fire resistance, and the fire source was set to 2 MW [65–67] to consider more dangerous fire conditions. Three measurement points were placed in the middle of the hill wall of the adjacent dwelling, the first house of the ancient village, at heights of 1.6 m, 4.6 m, and 7.6 m. A Y-plane slice was set on the orthographic plane. Furthermore, ambient temperature, wind speed, and simulation time parameters were the same as those in Section 2.3.1. The specific simulation parameters are shown in Figure 9c and Table 5.

Table 5. Specific parameter settings for the four types of hill wall scenarios.

Scenario	Fire Source	Fire Size	Grid Size	Grid Number	Ambient Temperature	Wind Direction	Wind Speed	Time
1	2 MW	1 m × 1 m	0.2 × 0.2 × 0.2 m	173,376	17 °C	East	1.5 m/s	1800 s
2	2 MW	1 m × 1 m	0.2 × 0.2 × 0.2 m	151,180	17 °C	East	1.5 m/s	1800 s
3	2 MW	1 m × 1 m	0.2 × 0.2 × 0.2 m	151,180	17 °C	East	1.5 m/s	1800 s
4	2 MW	1 m × 1 m	0.2 × 0.2 × 0.2 m	151,180	17 °C	East	1.5 m/s	1800 s

3. Results

3.1. Field Research Results

3.1.1. Wood Moisture Content and Residential Fire Loads

The investigation results on moisture content and fire load of the timber used in High-Chair village houses are shown in Figure 11 and Table A2. The average moisture content of the wood in these houses is 11%, which is "full dry wood" and easily causes a fire. The average amount of wood used in residential buildings is 0.26 m^3/m^2, 5.8 times more wood than used in modern buildings (0.045 m^3/m^2). The average fire fixed load density of the residential dwellings is 2133 MJ/m^2, about 5.1 times more than that of modern houses (420 MJ/m^2). The fire load density of residential houses will be greater if active loads such as household goods and furniture are considered.

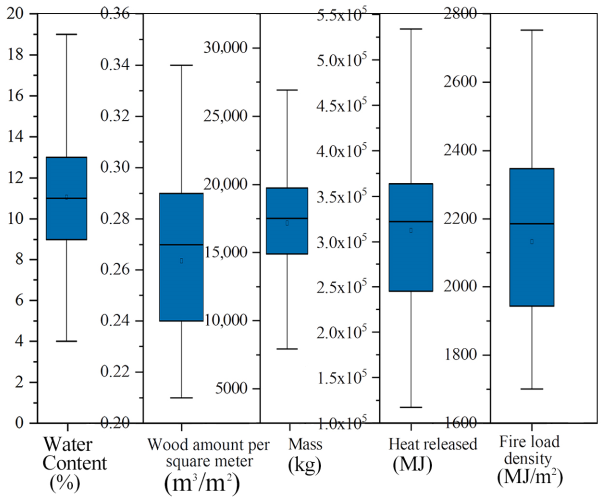


Figure 11. Investigation results on moisture content and fire load of the timber in High-Chair village houses.

3.1.2. Fire-Related Activities

Figure 12 depicts survey results on energy patterns and fire habits in High-Chair village. A total of 73.9% of residents cook with wood, and 87% store wood in their daily lives. Indoors, 91.3% of residents use fire, and 56.5% of residents smoke. Indoor and outdoor ritual fire behavior were performed by 30.4% and 91.3% of residents, respectively. 69.6% of the residents also have wood frame walls.

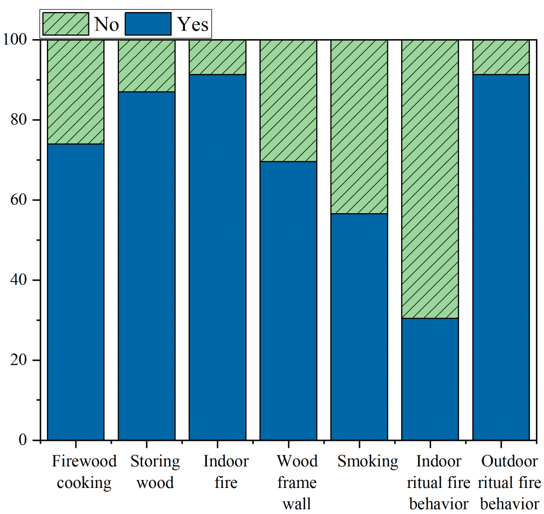


Figure 12. Survey results on energy patterns and fire habits in High-Chair village.

Highly flammable wood was abundantly used to build the dwellings, fire loads of the houses exceeded modern building standards, and the high frequency of multiple types of fire use by the residents created serious fire hazards in the village. However, it is amazing that no serious village fire accident has ever been recorded since it was built 600 years ago. This is certainly due to the dwellings' scientific and rational fire prevention strategies. It is worthwhile to study the strategies for fire prevention in dwellings created by our ancestors with limited knowledge and a multitude of experiences.

3.1.3. Patio Size

The investigation results on the patio dimensions of Jiaozi houses are shown in Figure 13. The patio length of the Jiaozi houses corresponds to the length of the residential openings, averaging 11 m. It is 4.09 m wide on average, 1.63 times wider than the High-Chair village streets (2.51 m) and twice as wide as the Lahao village streets (1.90 m). The patio has an average width-to-height ratio of 0.78, which is 1.63 times the D/H value of the High-Chair village streets (0.48), 1.53 times the D/H value of the Lahao village streets (0.51), and 1.34 times the D/H value of the Laodong village streets (0.58). The average width and D/H value of the patio exceed those of the street. The patio creates a partition between two dwellings, facilitates lighting and ventilation of the dwellings' interior, and blocks the direct spread of fire.

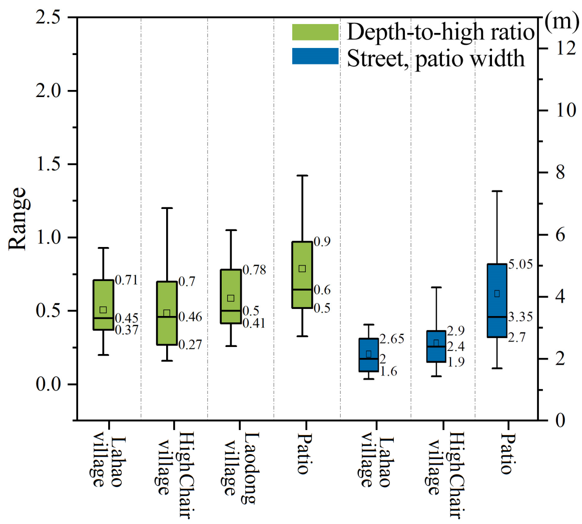


Figure 13. Investigation results on the patio dimensions of Jiaozi houses.

3.2. *Software Simulation Results*

3.2.1. Fire Simulation Results for Different Patio Layouts

- Combustion situation: First item

Figure 14 depicts simulated combustions of Jiaozi houses with various patios. In terms of combustion within 200 s, the four scenarios are similar. In scenario 1, the fire spread to the patio area in 400 s, half of the opposite side of the house ignited in 600 s, and the entire first floor on the opposite side ignited in 800–1000 s. The house on the other side burned for the next 800 s (Figure 14a). In scenario 2, at 400 s, the fire spread in the residential house of its source; at 1200 s, the entire first floor on the other side ignited, and over the following 600 s, the dwelling on the other side continued to burn (Figure 14b). In scenario 3, in 800 s, everything ignited on the other side of the first floor of the dwelling, at 200 s and 400 s earlier compared to scenarios 1 and 2, respectively (Figure 14c). In scenario 4, the fire always occurred in the dwelling containing the fire source within 1800 s, and the dwelling on the other side did not ignite (Figure 14d).

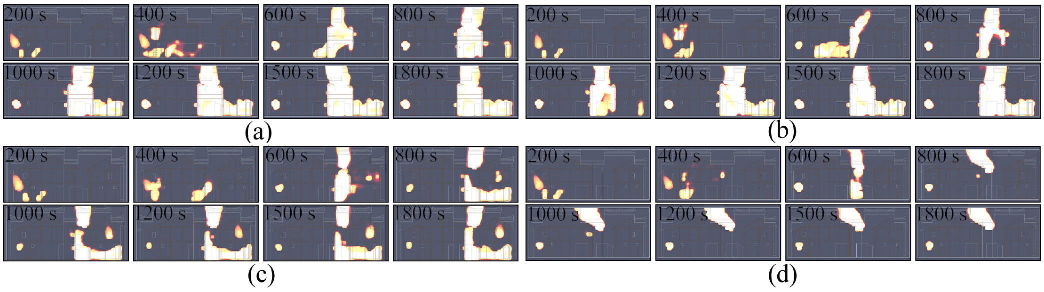


Figure 14. Simulated combustions of Jiaozi houses with different patios: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4.

- Wall temperature

The simulated wall temperatures in the four patio scenarios are shown in Figure 15. In Scenario 1, at 600 s, the temperature of the patio corridor exceeded 900 °C. At 900 s, the temperature of the adjacent dwelling's first floor exceeded 300 °C. During 1200–1800 s, full-scale combustion occurred on the first floor of the adjacent dwelling, and the temperature exceeded 900 °C. In Scenario 2, the fire did not spread to the adjacent dwelling at 600 s. At 900 s, the temperature of the wall near the patio of the adjacent dwelling exceeded 260 °C. During 1200–1800 s, the area where the temperature of the first floor of the adjacent dwelling exceeded 260 °C gradually increased. In Scenario 3, at 600 s, the wall near the patio of the adjacent dwelling had a temperature exceeding 260 °C, earlier than that in Scenario 2. The area where the temperature of the first floor adjacent to the patio exceeded 830 °C gradually increased between 900 and 1800 s. During 0–1800 s in scenario 4, the roof temperature of the adjacent dwelling near the patio was approximately 150 °C, and the temperature of the interior walls was unaffected. Scenario 4 was the most severe, followed by Scenario 2, Scenario 1, and Scenario 3.

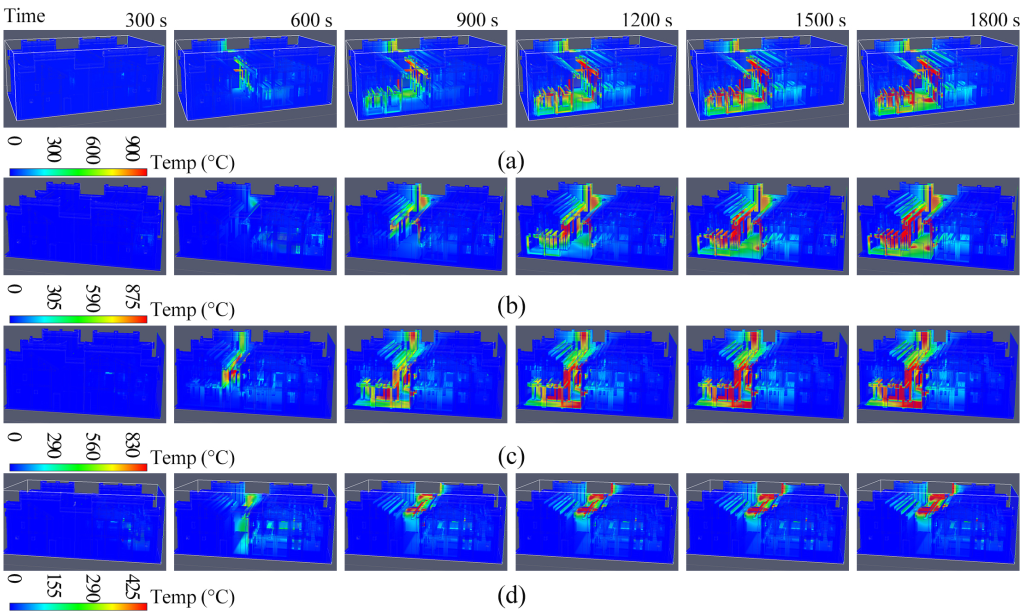


Figure 15. Simulated wall temperatures in the four patio scenarios: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4.

- Measurement point parameters

Temperature variation results with time for each measurement point are shown in Figure 16a. Scenario 1 showed a rapid temperature increase at measurement point 1 to the maximum (1000 °C) within 400–700 s, decreasing to 400 °C within 700–800 s, and fluctuating around 400 °C over the following 1000 s. Scenario 2 showed a slow increase in the temperature at measurement point 1 within 400–1000 s, a rapid increase to a maximum (about 680 °C) within 800–1200 s, and a fluctuating change near 680 °C over the next 600 s. Scenario 3 showed a rapid increase in temperature at measurement point 1 to a maximum (about 700 °C) within 400–900 s and fluctuating changes around 700 °C for the next 900 s. Scenario 4 showed the temperature at the three measurement points fluctuating around 20 °C throughout the simulation time. The curves of scenario 3 were the first to show a significant increase, followed by scenario 1, while scenario 4 changed the least. The four scenarios were affected by fire in descending order: scenario 3, scenario 1, scenario 2, and scenario 4.

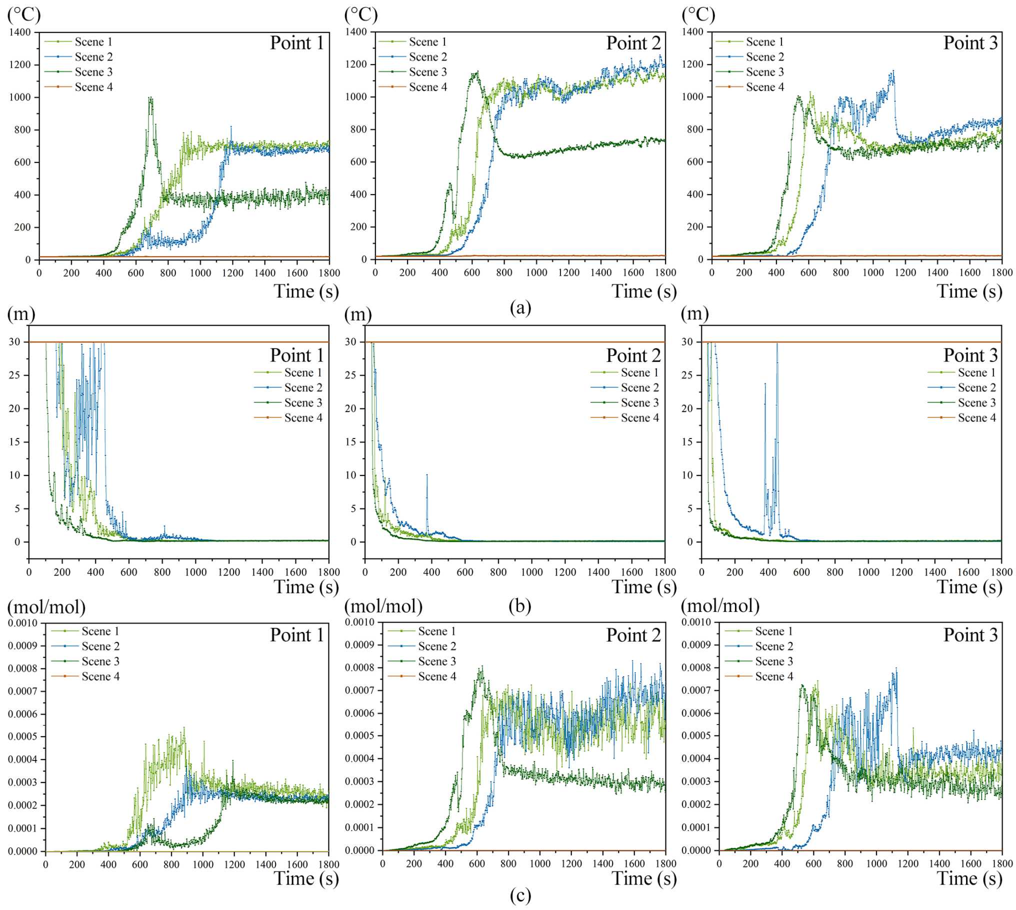


Figure 16. (**a**) Temperature variation results with time for each measurement point; (**b**) the visibility variation results of each measurement point with time; (**c**) and the CO concentration variation results of each measurement point with time.

Visibility variation results at each measurement point with time are shown in Figure 16b. The visibility variation sequence at each measurement point was the same as that of the temperature, and the visibility in scenario 3 rapidly decreased from 30 m to 0 m at the three measurement points. The visibility reduction rate at each measurement point in scenario 2 was less than those in scenario 1 and scenario 3. The visibility at each measurement point in scenario 4 fluctuated at 30 m. The trend of CO concentration with time for each measurement point was the same as that of the temperature, and visibility is shown in Figure 16c.

3.2.2. Fire Simulation Results for Different Hill Wall Forms

- Combustion situation

Figure 17 shows simulated fire combustions in dwellings with different hill wall forms. In scenarios 1 and 2, the fire-burning situation had no significant difference, and the dwelling adjacent to the fire source was unaffected by the fire throughout 1800 s (Figure 17a,b). In scenario 3, during 0–1000 s, a fire broke out in the dwelling containing the fire source and continued to burn. During 1000–1200 s, the fire spread to the adjacent residential roof area. During 1500–1800 s, the fire spread from the roof to the second-floor rooms, which were not completely destroyed (Figure 17c). Scenario 4 was the most severely affected. At 800 s, the adjacent dwelling's roof was completely ignited. During 1000–1800 s, the fire spread to the entire second floor of the adjacent dwelling (Figure 17d).

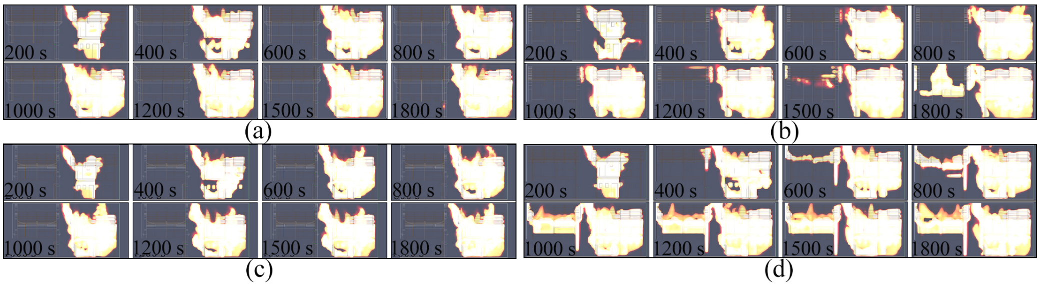


Figure 17. (**a**) Simulated fire combustion of dwellings with different hill wall forms: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4.

- Wall temperature

Figure 18 shows the simulated wall temperatures of dwellings with different hill wall forms. The simulation results in scenarios 1 and 2 were similar, with the temperature of the adjacent dwelling only exceeding 260 °C at the hill wall surface within 1800 s (Figure 18a,b). In scenario 3, the roof frame area was where the temperature mainly exceeded 260 °C. At 1200 s, about $^{1}{}_{3}$ of the roof frame exceeded 260 °C. At 1800 s, the area exceeding 260 °C remained mainly in the roof frame area, and the maximum temperature remained below 900 °C (Figure 18c). The fire most severely damaged the adjacent dwellings in scenario 4. At 600 s, the temperature on most of the roof frame of the adjacent dwellings exceeded 260 °C, and during 900–1800 s, the temperature of the entire roof frame and most of the second-floor areas exceeded 900 °C (Figure 18d). The fire in scenario 4 was the most severe, followed by the fire in scenario 3, while the fires in scenarios 1 and 2 were contained.

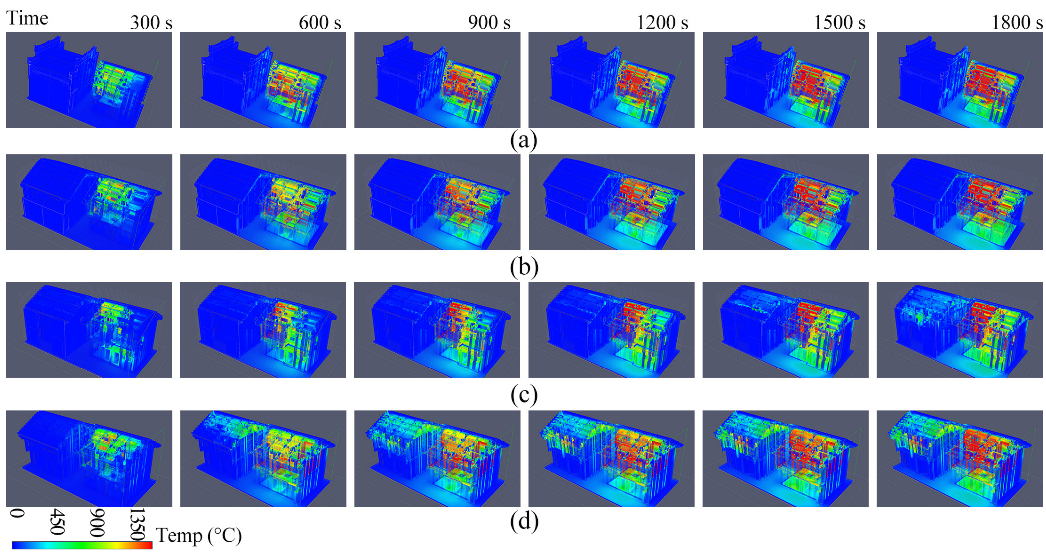


Figure 18. Simulated wall temperatures of dwellings with different hill wall forms: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4.

- Measurement point parameters

Temperature variation results with time for each measurement point are shown in Figure 19a. The temperature at measurement point 1 in the four scenarios did not change significantly with time and did not exceed 260 °C. The temperature at point 2 exceeded 260 °C in scenario 4, increasing rapidly to about 500 °C in 600–800 s, and then fluctuated and grew over the next 1000 s, but remained always less than 260 °C in scenarios 1, 3, and 4. The temperatures in all scenarios at measurement point 3 exceeded those at points 1 and 2, and all fluctuated and varied in the range of 20–400 °C. The temperatures at all times at measurement point 3 in scenario 1 were lower than those at points 2 and 3. The temperature at point 3 in scenario 4 exceeded 260 °C at 450 s with a steadily increasing trend for the next 1250 s.

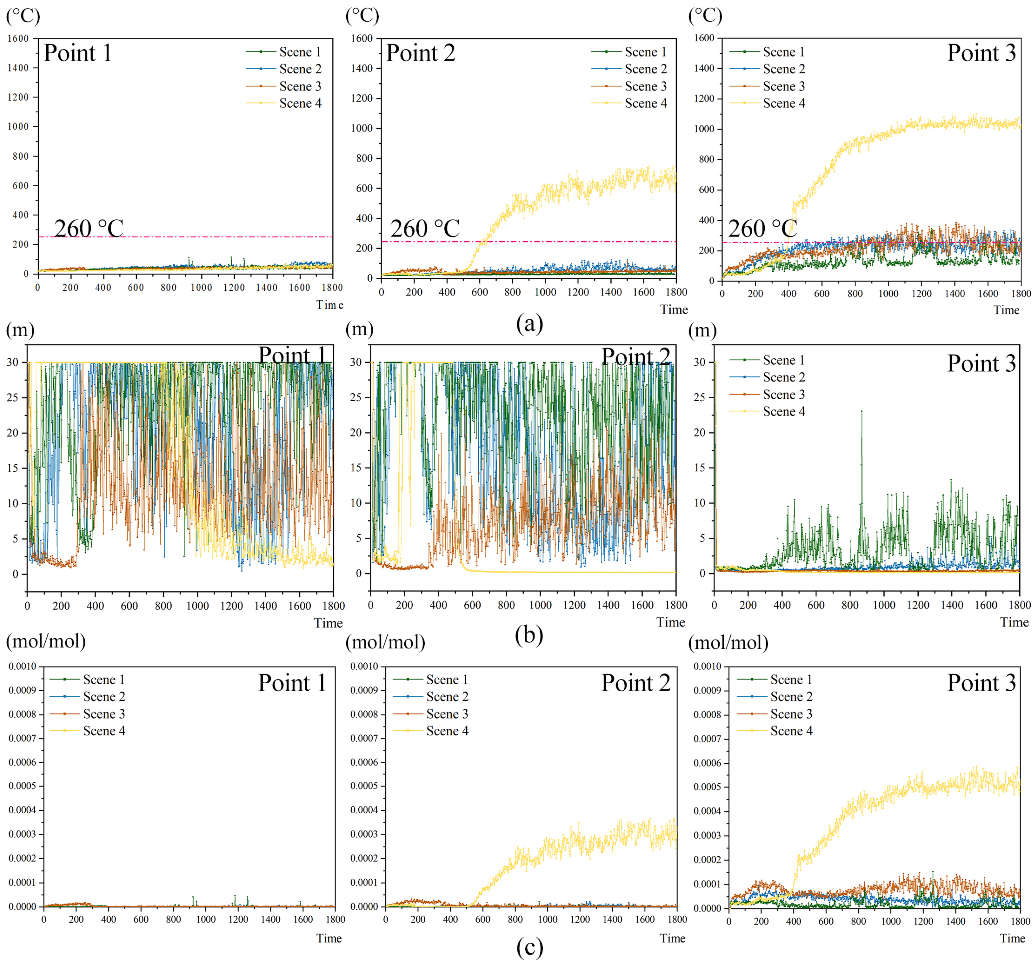


Figure 19. Results of fire parameter variations with time for each measurement point: (**a**) temperature; (**b**) visibility; (**c**) CO concentration.

Visibility at points 1 and 2 also showed fluctuating variations in all scenarios. Visibility at point 3 was most significantly affected. The visibility in all scenarios decreased to 0 m at 50 s at point 3. Scenario 1 showed fluctuations in the 0–25 m range from 400–1800 s, and its visibility was significantly better than that of the remaining three scenarios. Scenarios 3 and 4 had visibility of less than 2 m at all times. Scenarios 1–4 had visibility ranked from highest to lowest (Figure 19b). The concentration of CO at each measurement point varied with temperature. The fire affected the four scenarios in the following order: scenarios 1–4 in descending order (Figure 19c).

4. Discussion of the Traditional Fire Prevention Wisdom of Ancient Village Dwellings

4.1. Fire Prevention Culture

The fire prevention culture in ancient dwellings was slanted towards fire prevention by residents before effective fire prevention techniques existed. It warned the residents to always be aware of fire hazards and encouraged them to create technology-based fire prevention measures. Although these fire prevention cultures did not solve the fire prevention problem, they helped positively impact the consciousness aspect of fire prevention among ancestors with limited knowledge. When science and technology were undeveloped in the early days, ancestral knowledge of fire causes was limited, but these fire prevention cultures cannot be dismissed outright. These, along with other living cultures, form the core national culture and are integral to fire prevention in ancient dwellings.

4.2. Patio Form

As an important part of the ancient village houses, the patio is the essential outdoor area for daily activities and actively aids in fire prevention. Its average size in High-Chair village exceeds the street's average size, and its D/H value exceeds the street's. The temperature variation at each measurement point in a homocentric square patio (scenario 1) and a 日-shaped plan patio (scenario 2) is more dispersed than at points without a patio (Figure 20a), and the average visibility is lower than at those without a patio (scenario 3). The partition wall, in scenario 4, has the best fire protection, and adjacent dwellings are unaffected by the ignited dwelling (Figure 20b). The presence of the patio slows the spread of fire in directly adjacent dwellings, reducing the fire hazard (Figures A1 and A2). Furthermore, the outer parapet walls of Jiaozi houses are taller brick walls, and each dwelling serves as its own fire protection unit. It also prevents fire from spreading to adjacent dwellings.

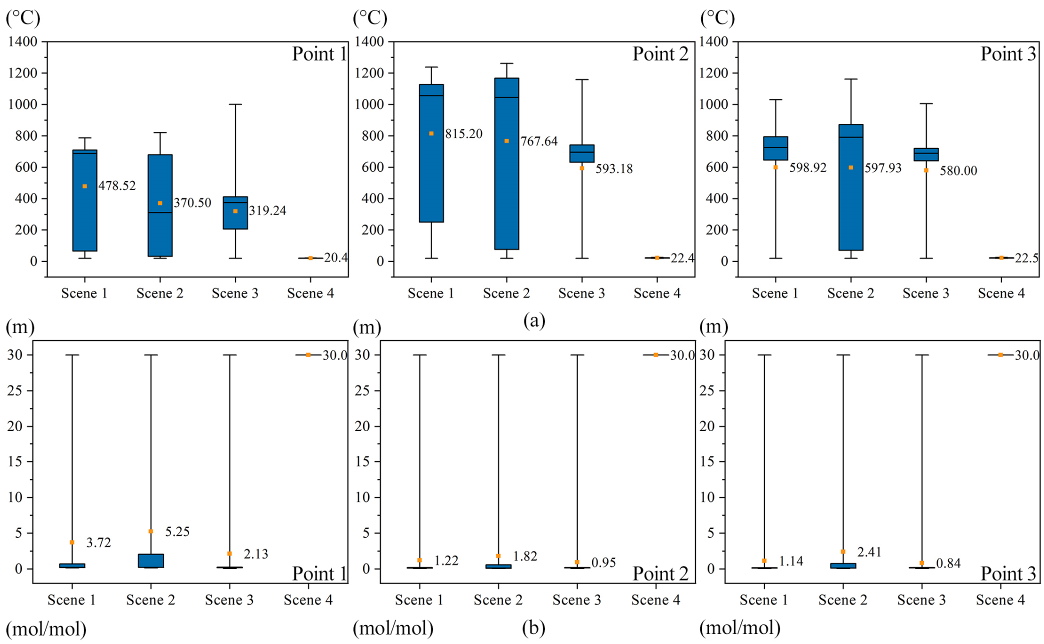


Figure 20. (**a**) Temperature analysis of each measurement point for the four patio scenarios during the simulation; (**b**) visibility analysis of each measurement point for the four scenarios.

4.3. Hill Wall Form

The spread of fire in ancient village dwellings in Western Hunan can be blocked using fire-resistant building materials such as bricks and stones, and the construction of outer parapets prevents the spread of fire. Due to smoke buoyancy, the temperature and smoke concentration at measurement points 3 were higher than those at measurement points 1 and 2. The dwellings in High-Chair village use walls projecting from the roof to block the spread of fire to the wooden roof frame structure, reducing the risk of fire (Figure 21). The fire and household sealing hill wall perform well in blocking fire. In scenario 3, compared to scenarios 1 and 2, the fire spread to the roof timber structure by igniting wood purlins (Figures A3 and A4). However, the hill wall over the roof effectively blocked the fire from spreading to the interior.

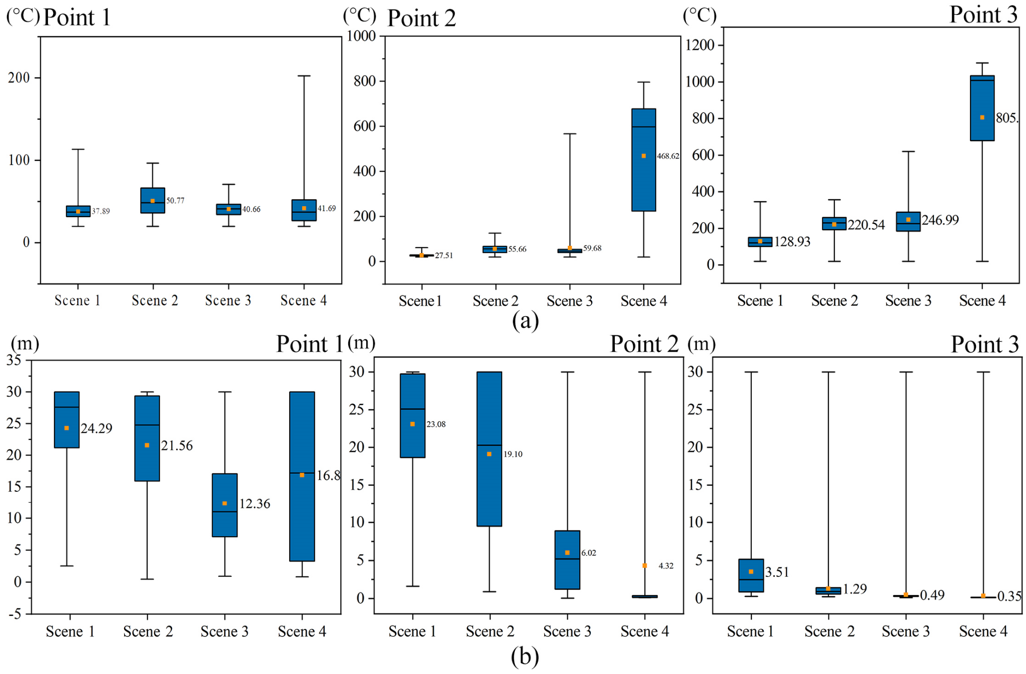


Figure 21. (**a**) Temperature analysis of each measurement point for the four hill wall scenarios; (**b**) visibility analysis of each measurement point for the four scenarios.

The ancient villages in Western Hunan are located in mountainous areas with abundant timber resources, and local inhabitants procure wood from local sources, making it a crucial building material for dwellings. Considering the fire factor, several wooden walls, columns, and roof frames were used for the interior, and exterior walls were built with bricks for proper fire resistance. This maximizes the optimum use of local natural resources. It creates a comfortable living environment while reducing the adverse effects of fire and also creates a unique architectural style.

5. Conclusions

This study investigates and assesses the fire risk in ancient High-Chair village, Western Hunan's first village. It identifies traditional fire prevention strategies and quantifies and reveals the science and rationality of traditional fire prevention measures. It even helps us understand why the ancient village has been preserved over millennia. Several significant findings are presented here, allowing the following conclusions to be reached.

- The survey results indicate a serious fire hazard in High-Chair village. The average moisture content of the wood in village houses is 11%, which is considered "fully dry" and can easily cause fires. The average amount of wood used in these houses (0.26 m^3/m^2) is 5.8 times the limit of wood used in modern buildings (0.045 m^3/m^2). The average fire fixed load density of residential houses (2133 MJ/m^2) exceeds that of modern residential buildings (420 MJ/m^2) by approximately 5.1 times. The percentage of residents using wood for cooking, storing wood, indoor fires, and smoking was 73.9%, 87%, 91.3%, and 56.5%, respectively. A serious fire incident has never been recorded in High-Chair Village since it was built 600 years ago, even with a fire load that surpasses modern disaster mitigation standards and a high frequency of multiple types of fire use by residents. The residential fire prevention strategies developed through hundreds of incidents deserve to be studied and learned.

- The residential fire prevention wisdom survey results indicate the existence of multiple types of fire prevention culture in the High-Chair village, including decorative patterns, architectural components, and living apparatus derived from residential legends and stories, the five elements of culture. The average width-to-height ratio of a typical residential cellar house patio in a High-Chair village dwelling (0.78) is also 1.63 times the street D/H value (0.48). The patio acts as an effective spatial partition between two dwellings, preventing fire spread. Meanwhile, the hill walls between High-Chair village's residential houses, with 300–400 mm thick masonry, serve as independent fire protection units, preventing fire from spreading to adjacent dwellings. A 6 m high fire escape is also built between two hill walls to aid in resident evacuation and fire rescue.
- Fire simulation scenario results show that temperature, visibility, and CO concentration at each measurement point on iambic and day patios are less affected by fire than points without patios. The patio also reduces fire risk by slowing the spread of fire directly to adjacent dwellings. Dwellings with fire-sealed gable walls block the spread of fire from adjacent dwellings. Dwellings with purlins projecting beyond the gable wall are unable to stop the spread of fire, and the fire spreads to the wood structure of the roof frame by igniting the purlins. Wall forms with hill walls extending beyond the roof are an effective fire prevention measure, and should be appreciated in rural development.
- The survival wisdom of the ancient village dwellings, formed through thousands of years, including ethnic culture, architectural layout, wall forms, and scientific and reasonable use of local building materials, is an important reference for modern rural construction, especially in remote mountainous areas. Currently, limited studies are revealing the response strategies of ancient buildings to various disasters. These priceless experiences, however, are part of our ancestors' cultural heritage. These response strategies are long-term, low-cost, and appropriate for the local cultural environment and climate. It is our responsibility to learn from our forefathers' wisdom, develop it, and pass it on to future generations.

These studies contribute to a clear understanding of the ancestral response to fire in ancient villages. However, this study has certain limitations. Factors such as daily activity behavior in the dwellings and indoor activity loads were not considered while creating this model. This study also reveals the scientific nature of fire prevention measures but does not provide a practical demonstration of their use in village construction. There are further studies possible on combining modern technology to create fire prevention and mitigation measures that include ethnic characteristics, regional culture, and good performance. Our ancestors also created a very rich and effective diverse disaster mitigation culture. Their preservation should begin in all regions, beginning in Western Hunan, and should include fire prevention. We must learn from history to build a better future.

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Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1. Patio forms in dwellings in High-Chair Village.

Num	Type	Owner	Depth of Patio/m	Patio Width/m	Patio Form	Opening
1	目-shaped plan	Y.J.	7.4	10.4	Irregular shape	3
2	目-shaped plan	Y.F.	6.3	11.4	Irregular shape	3
3	目-shaped plan	M.H.	7.2	9.6	Rectangular	3
4	目-shaped plan	Y.J.	7.1	10.5	Trapezoidal	3
5	回-shaped plan	Y.Y.	2.5	12.3	Trapezoidal	3
6	回-shaped plan	Y.F.	3.1	11.2	Rectangular	3
7	日-shaped plan	Y.F.	3.6	11.9	Trapezoidal	3
8	日-shaped plan	Y.R.	3.8	10.8	Rectangle	3
9	日-shaped plan	Y.Y.	2.3	5.9	Rectangle	2
10	日-shaped plan	Y.H.	2.4	10.1	Trapezoidal	3
11	日-shaped plan	Y.L.	3.1	12	Rectangle	3
12	日-shaped plan	Y.M.	2	10	Trapezoid	3
13	日-shaped plan	Q.B.	4.5	9.2	Trapezoidal	3
14	日-shaped plan	Y.R.	1.7	11.4	Rectangle	4
15	日-shaped plan	H.J.	9.1	11.8	Rectangle	3
16	日-shaped plan	Y.F.	5.8	6.2	Rectangle	3
17	日-shaped plan	W.Y.	3.2	12.5	Trapezoid	4
18	日-shaped plan	Y.G.	2.9	10.8	Trapezoid	3
19	日-shaped plan	Y.Y.	2.7	10.8	Trapezoidal	3
20	日-shaped plan	Y.Y.	2.9	10.9	Rectangle	3
21	日-shaped plan	Y.H.	2.2	12.1	Rectangle	3
22	日-shaped plan	W.H.	3	11.2	Rectangle	3
23	日-shaped plan	Y.Z.	2.5	11.6	Rectangle	3
24	日-shaped plan	Y.F.	4.5	11.8	Irregular shape	3
25	日-shaped plan	H.F.	2.1	10.8	Irregular shape	3
26	日-shaped plan	M.G.	3.4	14	Irregular shape	3
27	日-shaped plan	Y.R.	4.1	11.2	Rectangle	3
28	日-shaped plan	Y.R.	3.4	12.2	Trapezoidal	3
29	日-shaped plan	Y.G.	4	13	Rectangle	4
30	日-shaped plan	Y.Y.	2.7	15	Trapezoidal	5
31	日-shaped plan	Y.R.	3.5	12.8	Irregular shape	3
32	日-shaped plan	H.Y.	2.1	15.6	Trapezoidal	4
33	日-shaped plan	M.Y.	3.3	5.2	Irregular shape	1
34	日-shaped plan	Y.F.	2.7	10.5	Trapezoidal	3
35	日-shaped plan	Y.Y.	5.6	12.3	Rectangular	3
36	日-shaped plan	Y.Y.	4	16.5	Trapezoid	4
37	日-shaped plan	Y.X.	3.3	5.7	Trapezoidal	2
38	日-shaped plan	Y.R.	6.5	9.1	Rectangular	3
39	日-shaped plan	M.Y.	11.1	8.1	Trapezoidal	3
40	日-shaped plan	Y.Y.	6.2	15	Rectangle	5

Table A2. Investigation results of the fire loads of dwellings in High-Chair Village.

Owner	Wood Amount per Square Meter	Mass/(Kg)	Heat Released/(MJ)	Fire Load Density/(MJ/m^2)
Y.H.	0.29	17,569.2	323,273.28	2347.84
Y.R.	0.34	17,723.2	326,106.88	2752.64
Y.F.	0.29	18,044.4	332,016.96	2347.84
H.Y.	0.24	26,910.4	495,151.36	1943.04
Y.G.	0.3	15,298.8	281,497.92	2428.8

Table A2. *Cont.*

Owner	Wood Amount per Square Meter	Mass/(Kg)	Heat Released/(MJ)	Fire Load Density/(MJ/m^2)
Y.F.	0.27	22,008.8	404,961.92	2185.92
Y.R.	0.27	17,512	322,220.8	2185.92
J.G.	0.28	20,200.4	371,687.36	2266.88
Y.F.	0.28	18,216	335,174.4	2266.88
Y.R.	0.3	15,914.8	292,832.32	2428.8
M.Y.	0.32	6371.2	117,230.08	2590.72
Y.Y.	0.26	29,022.4	534,012.16	2104.96
H.J.	0.24	21,014.4	386,664.96	1943.04
Y.F.	0.22	17,446	321,006.4	1781.12
M.H.	0.22	16,038	295,099.2	1781.12
Y.Y.	0.27	12,504.8	230,088.32	2185.92
Y.J.	0.24	19,764.8	363,672.32	1943.04
Y.J.	0.29	18,801.2	345,942.08	2347.84
X.P.	0.23	12,012	221,020.8	1862.08
W.Y.	0.22	14,894	274,049.6	1781.12
Y.G.	0.21	13,323.2	245,146.88	1700.16
Y.G.	0.24	12,016.4	221,101.76	1943.04
Y.Y.	0.24	7924.4	145,808.96	1943.04

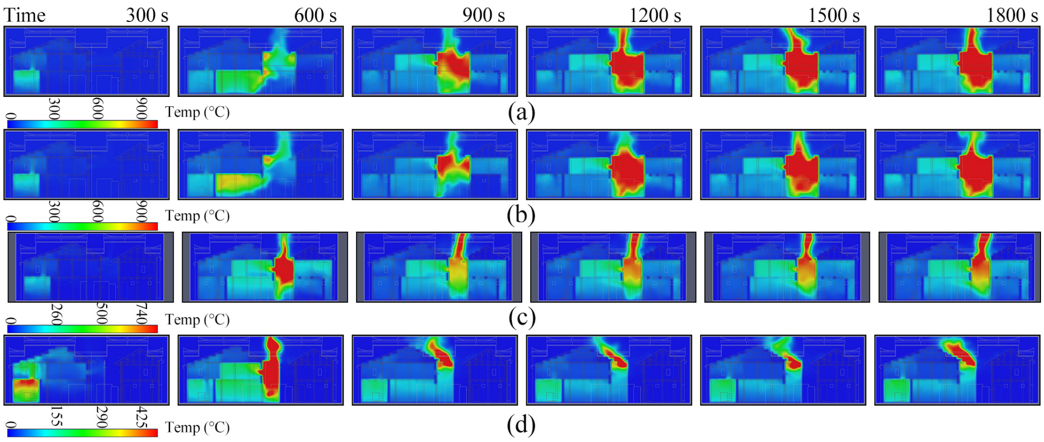

Figure A1. Simulated X-plane slice temperatures in dwellings with different patio layouts: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4.

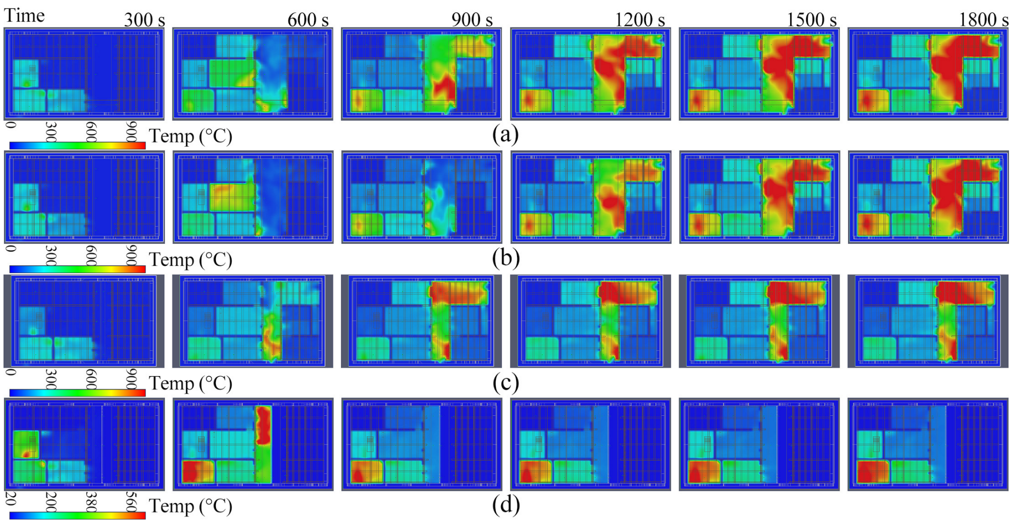

Figure A2. Simulated Z-plane slice temperatures in dwellings with different patio layouts: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4.

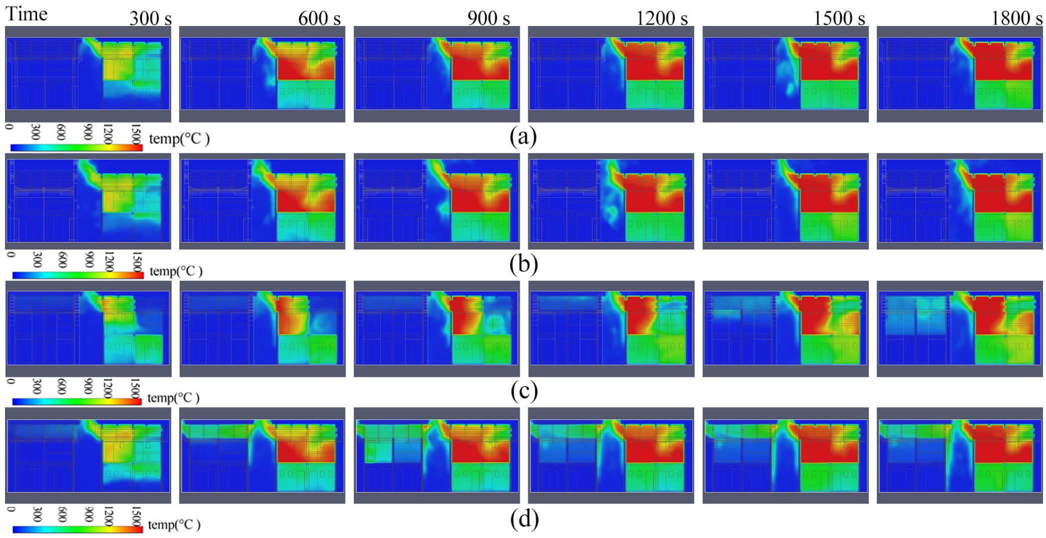

Figure A3. Simulated X-plane slice temperatures in dwellings with different hill wall forms: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4.

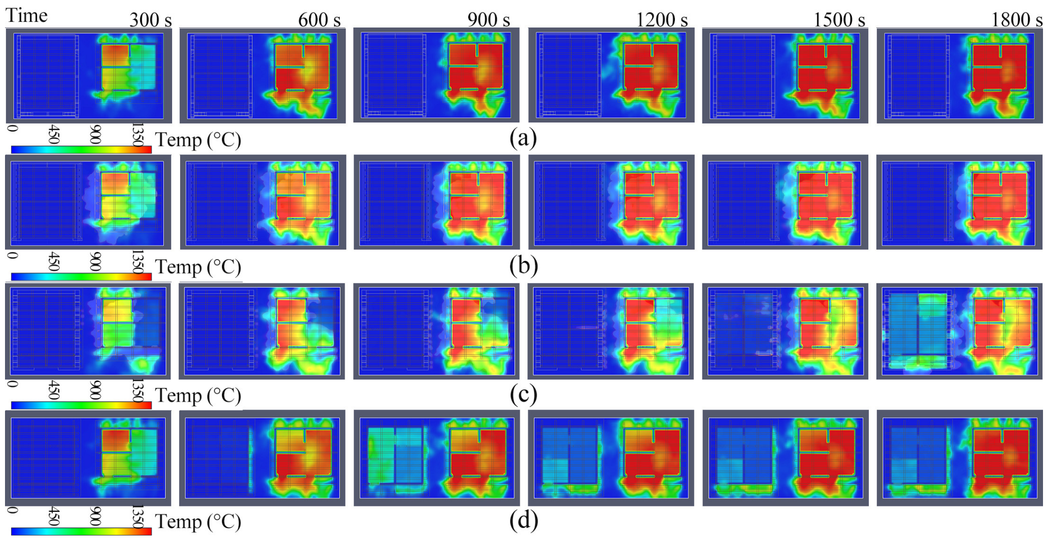

Figure A4. Simulated Z-plane slice temperatures in dwellings with different hill wall forms: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4.

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