Causes of Fires in Mountainous Villages and Design Methods for Its Prevention and Control

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Abstract: Fires in mountainous villages are characterized by "frequent ignition, rapid spread, and difficult extinguishment," posing significant threats to the lives and property, physical space, and cultural heritage of these communities. This paper investigates the causes of fires in mountainous villages through field surveys and semi-structured interviews, based on the theory of fire triangle. The study finds that the primary causes include villagers' improper use of fire and electricity, high fire loads, low fire resistance of buildings, dense village construction, inadequate fire protection facilities, and poor maintenance, along with challenging firefighting conditions. In response, the paper proposes specific design methods such as strengthening the separation between villages and forests, dividing fire protection clusters, and implementing multi-level isolation measures to control fire spread. These methods aim to provide a reference for fire protection planning and design in mountainous villages.

Keywords: Mountainous Villages; Causes of Fires; Design of Fire Prevention and Control; Fire Protection Cluster; Fire Separation

1. Introduction

Mountainous villages in China are built along mountains, clustered together, and inhabited by diverse ethnic groups, featuring picturesque landscapes that blend seamlessly with the natural terrain. They preserve traditional folk culture and carry the memories of social history, giving rise to numerous traditional villages. They are treasures in the cultural repository of China and an essential part of the world cultural heritage. However, in recent years, fires have frequently occurred in mountainous villages in China, some of which have even engulfed entire villages. For example, on February 14, 2021, Wengding Village in Yunnan Province, known as the "last primitive tribe," was destroyed by a massive fire, leaving only four houses standing. These fires not only pose a significant threat to people's lives and property but also cause irreversible damage to the local cultural landscape and inestimable losses to the rural cultural heritage. Therefore, addressing fire prevention and control in mountain villages is an urgent necessity.

2. Literature Review

Research on fire management in villages primarily focuses on fire prevention and firefighting, both of which rely on innovative management systems and modern firefighting technologies and facilities to achieve their goals. Regarding fire prevention, studies have mainly proposed measures such as multi-household joint defense [1], establishing a fire information network [2], and creating a collective help initial-fire-response system [3]. In terms of firefighting, the focus has been on improving firefighting equipment, intelligent electrical fire monitoring and early warning systems, enhancing water supply methods, and selecting micro fire trucks and firefighting tools suitable for the narrow roads in villages [4,5].

Research on rural fire protection planning and design is relatively scarce. In this area, scholars have proposed multi-scale fire prevention construction systems based on specific construction concepts or quantitative analysis methods, providing a comprehensive perspective for fire prevention construction in villages. For example, Zhao Ke, based on the "safe neighborhood" concept, constructed a fire protection system for Sichuan towns at the block-street-building complex levels [6].

Zhang Jian used quantitative methods to compare fire risks among various types of villages within a province, identified high-risk groups and dangerous buildings within village areas, and proposed a three-level fire prevention system at the provincial, village, and building levels [7]. Yang Longlong established a multi-scale fire prevention and control model at the room-courtyard-community-village levels [8]. These construction strategies include rational functional layout [9], strengthening fire separation in neighborhoods [10], improving building fire resistance [11], and constructing safe evacuation systems [12]. However, the strategies proposed in this field are often limited to general descriptions and lack specific, detailed design elaborations.

3. Methods

This study employs field surveys, semi-structured interviews, and the collection of local chronicles and government work reports to obtain information on the current spatial environment and fire protection construction of mountainous villages. It aims to uncover the characteristics of fires in these villages and uses the fire triangle theory to analyze the causes of fires and derive fire prevention and control design methods.

The fire triangle theory posits that a fire requires the simultaneous presence of an ignition source, combustible materials and an oxidizer [13]; the absence of any one of these elements will result in the fire being extinguished. The spread of a fire occurs as one combustible material ignites nearby combustible materials, causing the fire to propagate outward until the fuel is exhausted or the oxygen supply is depleted, at which point the fire will extinguish. In the context of mountainous village fires, wooden structures serve as the primary combustible materials, and the building that catches fire acts as the ignition source. Once a building ignites, the fire spreads within the village space. Oxygen, as the oxidizer, is abundantly present. The ignited building, through thermal radiation, ignites nearby structures, turning them into new ignition sources that continue to ignite surrounding buildings. This process results in the rapid outward spread of the fire until these buildings can no longer ignite their surroundings and are fully consumed, or until firefighting efforts intervene to extinguish the blaze.

4. The Characteristics and Causes of Fires in Mountainous Villages

4.1 Characteristics of Fires

From the perspective of the entire fire development process, the characteristics of fires in mountainous villages can be summarized as "frequent ignition, rapid spread, and difficult extinguishment." For example, in the Qiandongnan Miao and Dong Autonomous Prefecture, a mountainous region, rural areas experienced 1,210 fires between 2011 and 2020, accounting for 49.02% of the total fires in the region during this period [14]. This data illustrates the high frequency of village fires. The rapid spread of fires is evident as a wooden building can burn out completely within about ten minutes of ignition, and it takes less than five minutes for the fire to spread to nearby houses. The difficulty in extinguishing fires is reflected in the frequent malfunctions of firefighting facilities within the villages, making it challenging for villagers to rely on them to put out fires. Furthermore, the nearest township fire brigade usually requires at least half an hour to arrive at the scene, often finding themselves unable to do more than watch the fire and deal with the aftermath.

This combination of factors means that once a fire breaks out in a mountainous village, it can quickly develop into a large-scale disaster. The high frequency of fires provides a basis for their rapid spread, and the lack of timely and effective firefighting response objectively contributes to the further spread of the fire.

4.2 Causes of Fires

Through field investigations of the physical space and firefighting infrastructure in villages, as well as interviews with villagers and firefighting departments, it was found that the frequent occurrence of fires in mountainous villages is attributed to the improper use of fire and electricity by villagers and the large fire load of buildings. The rapid spread of fires is not only due to the large fire load of buildings but also to the low fire resistance rating of buildings and the dense spatial construction of villages. The difficulty in firefighting is caused by insufficient and poorly maintained firefighting facilities in villages, as well as difficulties in external firefighting rescue efforts (Figure 1). Specifically,

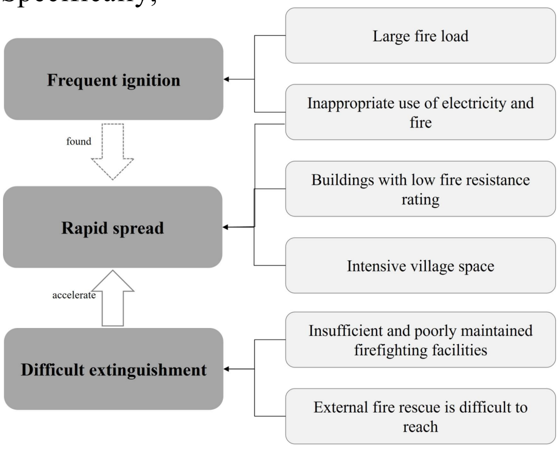

Figure 1. Causes of Fire in Mountainous Villages

(1) Improper Fire and Electricity Usage: Villagers' habits regarding fire usage remain primitive, often involving open flames for cooking and heating, which frequently lead to accidental fires. For instance, villagers may use fire pits to roast food, and the dripping grease can easily fuel the flames, leading to fires licking at the surrounding wooden flooring. Moreover, villagers often leave fires inadequately extinguished before leaving. On the other hand, modernization in lifestyle has led to a significant increase in electricity usage in households. However, the existing electrical circuits and wiring are often outdated, resulting in excessive electrical loads in villages, leading to frequent occurrences of overload, short circuits, and electrical leaks. Villagers' improper electrical behaviors, such as opting for low-quality electrical appliances due to economic constraints, illegally connecting wires for convenience, and installing them on wooden walls, further exacerbate the risk of fire. Additionally, the improper storage of agricultural machinery oil by villagers undoubtedly increases the fire load of buildings.

(2) Large Fire Load in Buildings: Buildings in mountainous villages typically utilize locally sourced materials and traditional construction methods, commonly opting for full wooden structures. Both structural and partition components within these buildings are made of wood, often accumulating large amounts of combustible household items indoors, resulting in a substantial overall fire load. The wooden walls and floors within these buildings not only fail to separate combustibles and control the fire but also contribute to its propagation. Combustible household items are usually scattered and exposed, making them susceptible to ignition when in contact with a heat source. Additionally, outside the buildings, roadsides, and squares often accumulate large quantities of combustible materials such as firewood, thatch, and construction materials, further increasing the fire load of the village.

(3) Low Fire Resistance of Buildings: Due to the prevalent use of full wooden structures, buildings lack effective containment of fires within confined spaces. The peripheral protective structures, such as exterior walls and doors, are made of wood, making it difficult to confine the fire within a single room, thereby facilitating its outward spread. While the roofs of buildings may consist of non-flammable tiles, the supporting components underneath are still made of wood. When a fire occurs, these lower components may burn and lose their supporting capacity, leading to localized collapse of roof tiles and subsequent upward propagation of flames.

(4) Dense Construction of Village Spaces: Limited available land for construction in mountainous villages often results in houses being built on sloping terrain. This leads to the construction of buildings in a step-by-step manner along contour lines, with small residential plots often fully occupied by houses. Consequently, village spaces become densely packed, with buildings interconnected by eaves and positioned in close proximity, failing to meet fire safety distances. This facilitates rapid spread of fires from one building to another once ignited (Figure 2).

Figure 2. Intensive Village Space

(5) Inadequate and Poorly Maintained

Firefighting Facilities: Outdoor fire hydrants in villages are insufficient in quantity and sparsely distributed, making it difficult to cover the entire village area adequately. Moreover, firefighting facilities are not effectively maintained. For instance, firefighting water is sometimes privately used by villagers without timely replenishment, and fire hydrants are not insulated, posing a risk of freezing during winter. Firefighting equipment such as water guns and hoses are often stored haphazardly, making it difficult to locate matching components during emergencies, significantly reducing the available firefighting facilities. Fire extinguishers stored in villagers' homes are often stored improperly and are mostly expired, compromising their effectiveness during fire incidents. These factors contribute to a high rate of damage to firefighting facilities, making them difficult to use effectively during fires.

(6) Challenges in Firefighting Rescue: Village firefighting and self-rescue capabilities are insufficient. Furthermore, external assistance in firefighting is unreliable. Mountainous villages are typically located in remote mountainous areas with limited accessibility, making it challenging for external fire brigade to arrive promptly. Additionally, the lack of firefighting access routes in the village, and even if firefighting vehicles reach the village, they often struggle to approach the fire scene, allowing the fire to continue spreading without timely suppression.

It can be seen that mountainous villages are unable to completely eliminate fires and rely on their own firefighting capabilities and external assistance to extinguish fires. Therefore, emphasis should be placed on enhancing the village's own resistance to fires, achieved through fire protection planning and design to control fire spread and minimize their scale. Based on the theory of fire triangle, the key to controlling fire spread lies in the differentiation of combustibles. The finer the division of combustibles, the smaller the impact area in the event of a fire. Therefore, it is necessary to implement layered isolation in villages filled with combustible buildings.

5. The Characteristics and Causes of Fires in Mountainous Villages

Fire prevention and control design in mountainous villages can be categorized into three spatial levels: village domain, village, and clusters. At the village domain level, emphasis should be placed on isolating the village from the surrounding natural environment. At the village level, fire protection clusters are designated to achieve isolation between different groups. At the cluster level, fire barriers are set up to isolate buildings from one another, thus achieving layered isolation within the village space.

5.1 Strengthening the Isolation between Villages and Forests

The isolation between villages and the surrounding natural environment, particularly forests, is crucial to prevent village fires from spreading into large forest fires and vice versa. Currently, mountainous villages often lack fire barriers between them and the adjacent forests. This can be strengthened through the following three approaches (Figure 3):

(1) Creating Fire Separation between Villages and Forests: By clearing trees along the edges of forests to create or widen firebreaks, space can be made for fire prevention zones. These zones could also serve as fire lanes. For villages facing land constraints, consideration can be given to converting any remaining or all available space into farmland, effectively replacing the forested areas surrounding the village and creating a firebreak between the village and the surrounding environment.

(2) Flame-retardant Treatment of Village Boundary Buildings: To enhance the fire isolation between villages and forests, the fire resistance of buildings at the boundaries of villages and forests should be strengthened to protect each unit from internal fire spillage and external fire invasion. Buildings at the village boundary, usually distant from the central area and not subject to architectural control, can be treated with fire-resistant measures such as converting wooden structures to brick structures or applying fire-resistant coatings to form a fire-resistant "protective village wall."

(3) Constructing Fireproof Forest Belts at Forest Boundaries: Fireproof Forest belts should be established along the boundaries of forests, using fire-resistant tree species. These belts should have a certain width and form a closed circle to constitute an ecological fire barrier for forests. Common fire-resistant tree species include camphor trees, evergreen oaks, tea oil trees, privets, and oleanders. Among

them, evergreen oaks are the most widely used fire-resistant tree species in southern China, while tea oil trees, waxberries, and koa trees have become common species for fire belts in Masson pine forests. These trees typically have evergreen leaves, thick epidermis, high water content, and low oil and wax content, giving them strong heat resistance and insulation properties.

Figure 3. Methods of Separating the Village from the Forest

5.2 Division into Fire Protection Clusters

By dividing densely clustered wooden buildings into smaller-scale clusters with isolation between them, the spread of fire can be contained within a single cluster, significantly reducing the extent of fire propagation. The following discusses the division principles, objects, tools, and methods:

(1) Division Principles: When conducting fire prevention renovations on built environments with historical significance, especially those with distinctive cultural and architectural heritage, caution should be exercised. Utilize existing resources to the greatest extent possible and minimize the need for demolition, adhering to the principle of minimal intervention.

(2) Division Objects: Dividing villages is not indiscriminate but focuses on areas with many fire hazards and concentrations of combustible materials. The former mainly includes production and processing areas and storage areas for flammable and explosive hazardous materials, while the latter refers to areas with concentrations of wooden buildings. Locations of high fire risks should be situated far from residential areas, and divisions should be finer to disperse them effectively.

(3) Division Tools: The division of villages can be achieved using firebreaks, linear spaces that effectively partition an area. These firebreaks should be at least 6 meters wide, and the boundaries of clusters should be made of flame-retardant materials or structures. If firebreaks are also intended for evacuation and rescue during disasters, they should be widened accordingly to ensure sufficient clearance height and turning radius for firefighting vehicles. Following the principle of minimal intervention, existing linear space resources within villages, such as rivers, green areas, ponds, farmland, roads, and squares, should be utilized as firebreaks. For areas where divisions cannot be achieved or where widths are insufficient, additional structures may need to be demolished to supplement them (Figure 4).

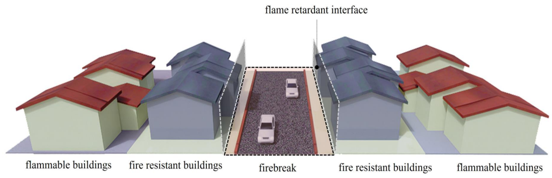

Figure 4. Design Requirements for Fire Barrier Belts

(4) Division Methods: The key issue here is selecting the division positions, i.e., where to place the firebreaks. This requires consideration of the cluster size and the types of buildings within the division positions. Cluster sizes should not be uniform but rather differentiated based on the fire resistance level of the buildings within them. For example, China's "Rural Fire Prevention Code" stipulates that the area occupied by buildings with higher fire resistance levels should not exceed 5000 square meters, while that of buildings with lower fire resistance levels should not exceed 3000 square meters. When dividing clusters of the same type, efforts should be made to ensure a more even distribution, which helps reduce the overall spread rate of the village. When selecting division positions, factors such as fire resistance level of buildings (wooden or masonry), their usage status (idle or in use), protection level (heritage or regular), and volume (main or accessory buildings) should be considered. Heritage buildings must not be altered, masonry buildings need no modification as they can serve as part of the firebreak, main wooden structures in use should be retained as much as possible, while unused or accessory wooden structures can be demolished. The optimal division position

should be chosen based on the cluster size and the types of buildings on the firebreak.

5.3 Setting up Fire Barriers

At the cluster level, where there are still concentrated groups of wooden buildings, it's essential to further divide them to reduce the overall risk of fire spread. This involves setting up fire barriers between buildings to minimize the ignition of surrounding structures. Fire barriers can be categorized into horizontal and vertical separation based on their position and orientation.

(1) Horizontal Separation: This is the more common method, involving the placement of vertical barriers in the horizontal direction. The principle is similar to dividing clusters. Horizontal separation involves setting up vertical barriers perpendicular to the ground to prevent fire spread. However, vertical separation, which controls fire propagation in the vertical direction, is often overlooked but crucial, especially for mountainous villages with terraced layouts. By setting up horizontal barriers, fire spread in the vertical direction can be effectively inhibited. Combining both horizontal and vertical fire barriers can significantly improve overall fire spread prevention.

1) Maintaining a fire-safe distance between buildings is fundamental. This may require partial demolition of structures or adjacent accessory buildings. If demolition is not feasible, reinforcing interfaces can prevent fire spread by: 2) Replacing at least one building interface with non-combustible material. 3) Installing a fire-resistant wall between two buildings. 4) Minimizing openings between walls and staggering their positions to prevent direct exposure. 5) Fireproof interfaces by converting at least one into a fire-resistant composite material, such as double-layered wood with galvanized steel sheets or applying fire-retardant coatings. 6) Considering the installation of a fire curtain on at least one building interface if conditions permit. Enhanced Measures: Combinations of distance and interface reinforcement can create effective fire barriers. For example: 7) A distance plus two fire-resistant interfaces form a traditional alley used in ancient China for fire isolation and rescue, creating a standard small-scale firebreak. 8) Distance plus two interfaces plus a top interface form a fire-resistant building. Therefore, fire-resistant buildings can be used to isolate two wooden structures effectively. This comprehensive approach to setting up horizontal fire barriers significantly mitigates the risk of fire spread between buildings (Figure 5).

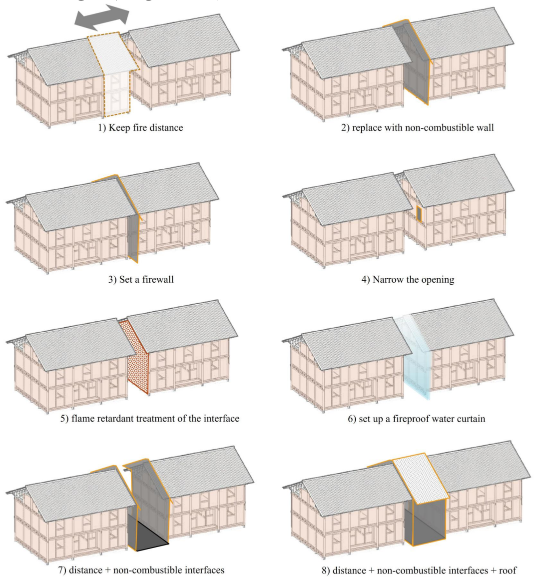

Figure 5. Methods of Setting Horizontal Partitions between Buildings

(2) Vertical Separation: vertical separation relies on installing multiple protruding components or blocks vertically to prevent the spread of fire upwards. The components or blocks that can be installed include:

1) Verandas: Covered outdoor spaces along the sides of buildings.

2) Cornices: Lateral components beyond the walls.

3) Overhanging bulges: Extensions or projections from the main structure.

4) Eaves: Overhanging edges of a roof.

5) Additionally, existing roof structures that inherently possess fire isolation functionality should be considered. However, it's essential to note that the supporting components of these structures, often exposed wooden rafters and beams, can become compromised if ignited. In such cases, the upper parts of the protruding components or blocks may collapse, losing their ability to prevent the spread of fire. Therefore, it's necessary to treat these supporting components with fire-resistant coatings, such as fire-retardant sprays, or encapsulate them with non-combustible materials. Implementing vertical separation effectively enhances the ability to contain fire spread within a building cluster (Figure 6).

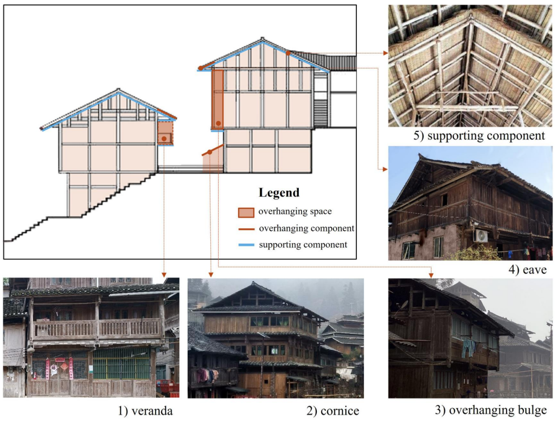

Figure 6. Methods of Setting Vertical Partitions between Buildings

6. Conclusion

This study, employing methods such as field surveys and semi-structured interviews, and guided by the theory of fire triangle, reveals that the causes of fires in mountainous villages stem from several factors: improper use of fire and electricity by villagers, high fire loads, low fire resistance rating of buildings, intensive village space, inadequate and poorly maintained firefighting facilities, and challenges in firefighting efforts. In response, the study proposes a multi-level isolation design strategy, including strengthening the isolation between villages and forests, dividing fire protection clusters, and implementing fire barriers. These strategies aim to provide support for firefighting planning and design in mountainous villages. However, these are primarily passive spatial fire prevention strategies. They should be complemented by proactive firefighting techniques such as intelligent firefighting technology and applicable firefighting facilities, along with efficient firefighting management measures, to effectively fortify the fire line in mountainous villages.

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