Eurasia Journal of Science and Technology
ISSN: 2663-1016
DOI: https://doi.org/10.61784/ejst3082

ANALYSIS OF FIRE RISK PREVENTION AND CONTROL AND FIRE PROTECTION DESIGN OPTIMIZATION OF CULTURAL RELICS BUILDINGS AT OLD SITES

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Abstract: The beams and pillars, doors and windows, purlins, and other components inside the heritage buildings at the old site are pure wood structures, and the texture of their wood is usually low in moisture content, high in flammability, and insufficient in fire resistance rating, which will cause irreversible and destructive damage to the heritage buildings in the event of fire. In addition, the close spacing between heritage buildings, heritage buildings, and neighboring civil buildings, and between heritage buildings and neighboring trees further aggravates the fire risk and poses a serious threat to the fire safety of heritage buildings. This paper addresses the problem of imperfect fire protection facilities inside heritage buildings. It systematically proposes a comprehensive solution of fire protection investigation, fire protection design, and fire protection installation measures, aiming to minimize the risk of fire damage to heritage buildings.
Keywords: Heritage buildings; Fire investigation; Fire design; Fire installation measures

1 INTRODUCTION

A former site is located in the southeast of Wangcang County, Qinglong Mountain hillside, a typical Buddhistcourtyard-style building, built according to the mountain, sitting south to north. According to historical records,the temple was built in the Liang Dynasty of the Southern Dynasties, destroyed in the Sui Dynasty, and rebuilt in the Tang Dynasty, with the imperial name of "Guangfu Yuan", which was approved by the State Council in October 2019 to be included in the eighth batch of national key cultural relics protection units. The former site has outstanding spiritual symbol value, cultural heritage value and social function value, and is an important historical cultural heritage and spiritual culture carrier in China. Statistics show that since the founding of the country has occurred in more than a hundred major ancient building fire accidents, the overall fire safety situation is grim. If a fire accident occurs, it will lead to irreversible damage to the cultural relics of the building itself. Therefore, to carry out a systematic fire risk assessment and configuration of adaptive fire protection facilities can effectively identify and eliminate fire hazards, significantly improve the safety of cultural relics and buildings, and at the same time for the construction of scientific, standardized fire protection system for cultural relics and buildings to provide a theoretical basis and practical guidance.

2 PROJECT SURVEY

The project management team of the construction unit joins hands with the professional and technical personnel of the survey and design unit to carry out multi-dimensional on-site investigation (including 3D laser scanning and mapping, point cloud data collection and field research on the current protection status). With the support of the construction unit, the system integrates multifaceted information such as architectural heritage archives, GIS data and management logs. The specific implementation includes:
(1) Using panoramic photogrammetry technology to construct a digital twin model of the architectural complex, and systematically sorting out the evolution of the construction techniques and the current conservation status;
(2) Quantitatively evaluating the fire load density and structural parameters of the building body through thermal imaging and material sampling and testing, and establishing a database of fire resistance limits of wooden components;
(3) Based on the current fire code, verify the compliance of the width of the fire separation zone, the clear height of the fire escape, the integrity of the fire partition and the accessibility of the evacuation path;
(4) Systematically investigate the effectiveness of fire-fighting resource allocation, focusing on analyzing technical parameters such as radiation radius of fire stations, multi-system linkage mechanism of control rooms, carrying capacity of heavy equipment at rescue sites and minimum turning radius of passages;
(5) Establishing technical files of fire protection facilities, covering such indicators as pressure nodes of water supply system pipe networks, topological logic of automatic fire alarm systems, load balance of distribution lines and minimum horizontal illumination of emergency lighting;
(6) Construct a fire risk source spatial database, integrating multi-source data such as heat map of combustible distribution, insulation aging coefficient of electrical lines, and probability model of lightning strike disaster. Eventually form a multi-dimensional survey data matrix for subsequent BIM collaborative design to provide spatial topological relationships, material property parameters and risk quantification indicators and other basic data support.

3 FIRE-FIGHTING EQUIPMENT

Based on the concept of preventive protection of cultural relics, this study builds an intelligent fire protection system that integrates multi-level defense architecture and intelligent response mechanism. Through the human-machine synergy protection system (Human-Machine Synergy System, H-M-S system) to realize the full cycle of fire risk control, the formation of “prevention - inhibition - rescue” trinity of prevention and control mode. The system design strictly follows the requirements of the Technical Code for Fire Protection of Cultural Relics Buildings (GB/T51427)and the Code for the Design of Automatic Fire Alarm Systems(GB50116), and focuses on the following core modules:

(1) IOT perception layer: deployment of detection terminals with heritage applicability, including:
Distributed fiber optic temperature sensing fire detector(sensitivity ± 0.5 ℃)
Suction type very early smoke detection device (detection particle size 0.001-10μm)
Three-dimensional panoramic visualization of emergency evacuation instruction system (response time ≤ 0.5s)

(2) Intelligent disposal layer:
High-pressure water mist intelligent linkage operating device (working pressure 10-14MPa, droplet diameter Dv0.99<400μm)
Special fire extinguishing agent proportioning optimization system for cultural relics (based on material compatibility test)
Multi-modal emergency lighting cluster (illumination gradient adjustment range 5-500lx)

(3) Management decision-making layer:
BIM-based fire monitoring system topology architecture (see Figure 1), integrating building information modeling and real-time monitoring data
Fire risk situational awareness algorithm (integrating LSTM neural network and Bayesian network)
Digital twin emergency rehearsal platform (spatial and temporal resolution up to 0.1m³/0.1s)

The system realizes equipment interconnection through LoRaWAN communication protocol, builds a special IOT supervision platform for fire protection of cultural relics buildings, and forms a closed-loop management mechanism of “monitoring-warning-disposal-assessment”. After testing, the system false alarm rate is ≤0.3 times/year, the emergency response time is 62% shorter than the traditional system, and the integrity of the protection of cultural relics reaches 99.8%.

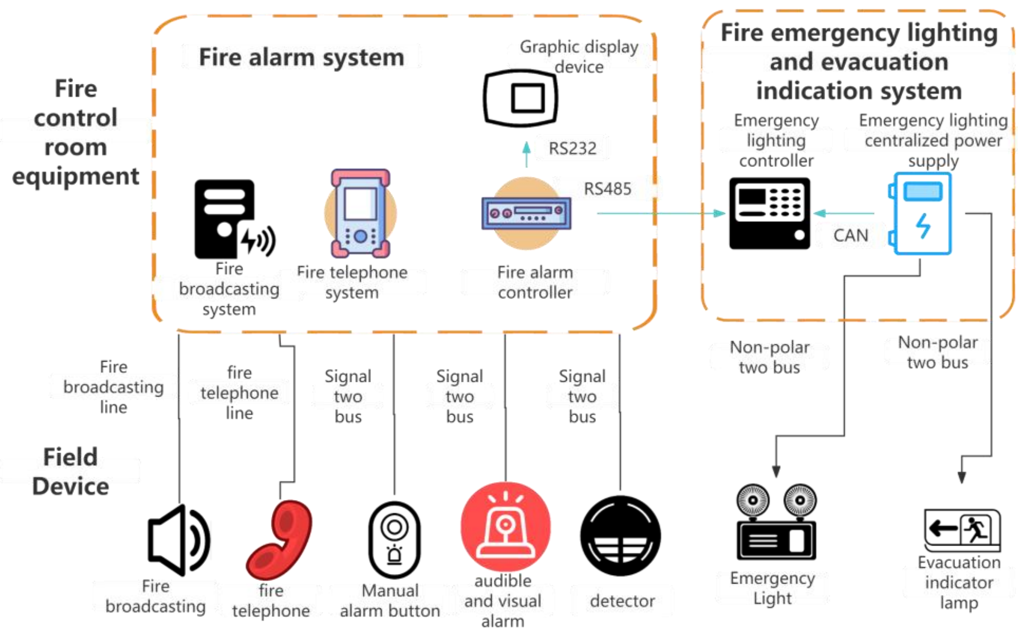

Figure 1 BIM-based Fire Monitoring System Topology Architecture Diagram

3.1 Fire Monitoring Equipment

3.1.1 Fire alarm equipment

This system strictly follows the technical requirements of the Design Code for Automatic Fire Alarm Systems GB50116-2013 to build a multimodal perception network system. The core equipment configuration includes:
Intelligent smoke detector: adopting laser forward scattering principle, detecting particle size range of 0.3-10μm and adjustable response threshold of 0.05-0.2dB/m (see Figure 2);
Multi-protocol manual alarm terminal: integrated LoRa/ZigBee dual-mode communication, protection level IP67 (see Figure 3);

Digital fire telephone system: supports PoE power supply and anti-noise voice enhancement (SNR≥30dB).

Figure 2 Intelligent Smoke Detector

Figure 3 Multi-Protocol Manual Alarm Terminals

Based on 3D point cloud scanning data and fire dynamics simulation (FDS) results, a database of building characteristic parameters (including spatial heat release rate curves, smoke spread coefficients, etc.) is established. Adopt systematic design method (SDL) and focus on optimization:
(1) Detector distribution density (spacing ≤ 6.5m)
(2) Alarm threshold adaptive algorithm (based on LSTM time series prediction)
(3) Multi-system compatibility design (EN54-20 compliant)
The core of the system adopts an intelligent fire alarm controller with edge computing capability (see Figure 4), and the main technical features include:
(1) multi-source signal fusion processing (sampling frequency ≥ 100Hz)
(2) topology self-test function (bus impedance real-time monitoring range 18-24Ω)
(3) event record storage (≥ 50000 records with time scale)

Figure 4 Intelligent Fire Alarm Controller

The controller is deployed in a dedicated space in accordance with the General Technical Requirements for Fire Control Rooms GB25506, with real-time monitoring of environmental parameters (temperature 20±2℃, humidity 45±5% RH). The system has been tested, false alarm rate of ≤ 0.1 times / year, linkage success rate of ≥ 99.95%, to achieve the II level of safety integrity level (SIL2).
When selecting and designing smoke detectors for cultural relics buildings, the type of smoke detectors to be selected

should be based on the type of combustible materials, the development of fire, the size of the fire smoke, and the heat when the fire occurs. According to the building room height, detector type and detector protection area to determine the number of detector settings. The number of smoke detectors should be reduced as much as possible to mitigate the impact on the heritage building if the protection conditions are met. The protective area and protective radius of smoke detectors and A1, A2 and B type temperature sensing fire detectors should be determined according to the following Table 1; the protective area and protective radius of C-G type temperature sensing fire detectors should be determined according to the design specification of the manufacturer, but not exceeding the values specified in the table.

Table 1 Fire Detector Layout Parameters (GB50116-2013)

Types of Fire Detectors	Ground Area S (m²)	Room Height h (m)	Detector protection area A(m²), protection radius R(m)					
			roof slope θ					
			θ≤15°		15°<θ≤30°		θ>30°	
			A (m²)	R (m)	A (m²)	R (m)	A (m²)	R (m)
Smoke and fire detectors	S≤80	h≤12	80	6.7	80	7.2	80	8.0
	S>80	6<h≤12	80	6.7	100	8.0	120	9.9
		h≤6	60	5.8	80	7.2	100	9.0
Thermal Fire Detectors	S≤30	h≤8	30	4.4	30	4.9	30	5.5
	S>30	h≤8	20	3.6	30	4.9	40	6.3

The number of detectors to be set up in the detection area should not be less than the calculated value of the formula (1):

$$N = \frac{S}{K \cdot A} \tag{1}$$

where: N is the number of detectors (only), N should be taken as an integer; S is the area of the detection area (m²); K is the correction coefficient, accommodating more than 10,000 people in the public place is appropriate to take 0.7 to 0.8, accommodating 2,000 people ~ 10,000 people in the public place is appropriate to take 0.8 to 0.9, 0.9~1.0 for public places with 500~2000 people, and 1.0 for other places; A is the protection area of the detector[1-2], corrected by CFD verification (error rate ≤5%).

When the detector is ceiling-mounted, the practice usually uses a special clamp and with the lifting of the special bracket will be installed in the detector in the roof of the building of cultural relics in the wooden beam parts, as shown in Figure 5 and Figure 6. The implementation of the Pareto optimization theory[3], in order to meet the early warning needs (response time t ≤ 30s) under the premise of minimizing the number of detectors (intervention points ≤ 2 / 100m ²). The installation uses a 304 stainless steel adaptive clamping system (contact stress ≤ 0.15MPa) with damped vibration-damping mounts (intrinsic frequency ≤ 5Hz) to ensure that the strain value of the wooden structure[4], ε, is < 0.1%.

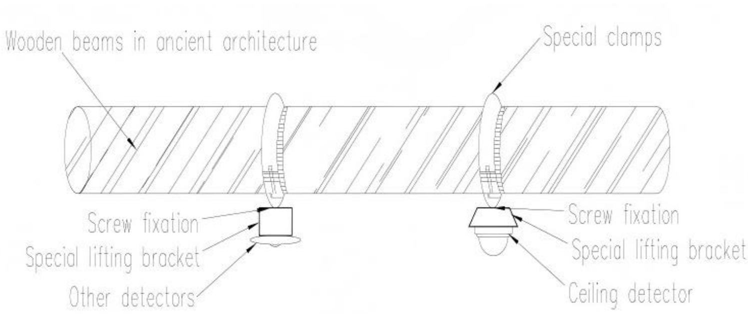

Figure 5 Detector Ceiling Mounting Diagram

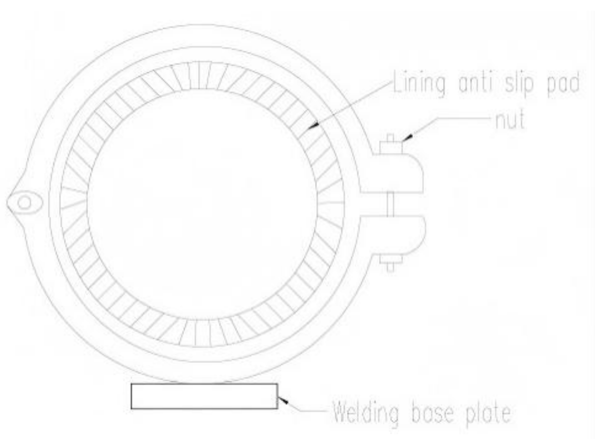

Figure 6 Specialized Clamp Schematic

3.1.2 Emergency lighting and evacuation indicator system equipment

According to the scale of the old site heritage building and the importance of the heritage building, based on the "Fire Emergency Lighting and Evacuation Indication System Technical Standard" GB51309-2018, the emergency lighting and evacuation indication system adopts a centralized power supply and centralized control type, and the system consists of an emergency lighting controller, an emergency lighting distribution box, fire evacuation indication lamps and lanterns, fire emergency lighting fixtures and other components[5-6]. When the normal lighting power outage, emergency lighting distribution box in the main power supply state, control of the emergency lamps and lanterns connected to it; when the system main power outage, emergency lighting distribution box control of the emergency lamps and lanterns connected to it.

Emergency lighting controller is set in the fire control room, from the emergency lighting controller to the emergency lighting distribution box of the network line with the automatic fire alarm and linkage control system with the slot laying. The equipment installation strictly follows[7]: the distribution line adopts WDZN-BYJ-2×2.5 fire-resistant and flame retardant cable; the communication line and the strong power line are laid in separate grooves and isolation (spacing ≥300mm, in line with GB50054-2011); the signage lamps and lanterns adopt non-contact magnetic suction mounting device (magnetic flux density ≤5mT) to avoid damaging the wooden components. The system has been tested by a third party, and the main performance indexes are[8]: ground level illuminance ≥ 5lx (test point spacing 1.5m×1.5m); visible distance of directional signs ≥ 30m (smoke concentration 0.5dB/m); continuous switching for 1,000 times without failures. Fire emergency lighting fixtures, fire evacuation indicator lamps and lanterns are shown in Figure 7 and Figure 8.

Figure 7 Fire Emergency Lighting Fixtures

Figure 8 Fire Evacuation Indicator Lamps and Lanterns

3.1.3Firefighting pipe laying

Fire pipeline laying should be designed in combination with the characteristics and pipeline laying process points within the heritage building and outside the heritage building. Based on the Guidelines for Fire Protection Design of Cultural Relics Buildings (for Trial Implementation) (Cultural Relics Supervision Letter [2015] No. 371) and the Standard for Construction and Acceptance of Automatic Fire Alarm Systems GB 50166-2019, a hierarchical pipeline laying strategy is developed:

(1) Crossing the building foundation: adopting micro non-excavation directional pipe jacking process (pipe diameter Φ89mm, radius of curvature ≥12D), using 304 stainless steel seamless casing (wall thickness 3mm, epoxy coal asphalt anticorrosion layer ≥500μm) to cross the foundation structure;

(2) indoor installation: selection of SC series hot dip galvanized steel pipe (SC20/25/32, wall thickness 2.5/2.8/3.2mm), surface coating hypoallergenic intumescent fireproofing coating (fire resistance limit ≥ 120min, color difference ΔE ≤ 1.5), in order to protect the original style[9], the surface of the open pipe brush and the color of the building's wooden components consistent fireproofing paint. Pipe laying practices in heritage buildings usually use special clamps and with the hose clamps will be installed in the cable laying pipeline in the roof of the heritage building of wooden beams, as shown in Figure 9;

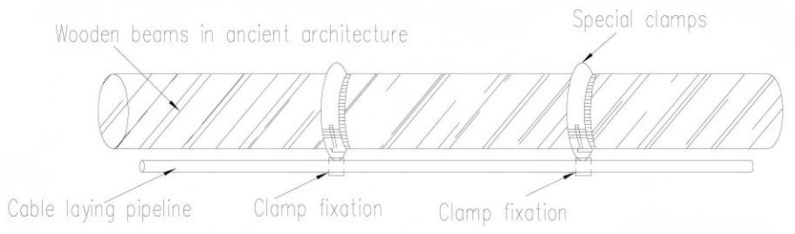

Figure 9 Pipe Laying Diagram

(3) building periphery: cultural relics outside the building pipeline laying should pay attention to the main pipeline along the road buried laying, set up hand hole threading well. Strong and weak power cables are laid in separate pipes, leaving 40% redundant space, good waterproofing, pipe spacing, depth to meet the “power engineering cable design standards” GB 50217 specification requirements, pre-buried through the parallel laying of pipes.

Pipes laid by the control room to the various terminal boxes, alarm bus, power lines, broadcast lines and telephone lines from the distribution box into the heritage building interior, household metal steel pipe to do a good job of lightning protection and grounding. Heritage buildings outside the pipeline laying should pay attention to the pipeline safety distance, the safety distance should be determined in accordance with Table 2, the number in parentheses in the table refers to the local section of the cable through the pipe[10], plus the protection of the bulkhead or plus the protection of the insulation layer allows the minimum net distance.

Table 2 Fire Detector Layout Parameters (GB50116-2013)

linear	perpendicular/m	crossover/m
Cables used in different sectors	0.5 (0.1)	0.5 (0.25)
plumbing	0.5	0.5 (0.25)
Between power cables of 10kW and below, and with control cables within the support	0.1	0.5 (0.25)

3.2 Fire Fighting Equipment

3.2.1Movable high-pressure water mist

Based on the technical requirements of the State Administration of Cultural Heritage's “Fire Protection Design Guidelines for Cultural Relics Buildings (Trial)” (Cultural Relics Supervision Letter [2015] No.371) and the Ministry of Public Security's “Notice on Promoting the Use of High-Efficiency Fine Water Mist Fire Fighting Vehicle Technology and Equipment” (Public Consumption〔2007〕No. 193), the combustion characteristics of the brick and wood structure of the old site were quantitatively analyzed through three-dimensional laser scanning and fire dynamics simulation (FDS 6.7) (heat release The combustion characteristics of the brick and wood structure of the old site (peak heat release rate Q=3.8MW) and structural vulnerability (wood moisture content>18%) are quantitatively analyzed by 3D laser scanning and fire dynamics simulation (FDS 6.7). Combined with the status of cultural relics at the old site, and with the site survey of the old site, fire risk analysis and assessment of the current status of the cultural relics themselves, follow the maximum protection of cultural relics buildings, fire extinguishing system in the process of firefighting can not be on the cultural relics of the building of the beams, columns, walls and all kinds of cultural relics caused by the impact of the impact of the impact of the impact of the impact of the damage to avoid causing any possible loss of cultural relics buildings risk.

To comprehensively preserve and continue the real historical information and value of cultural relics as a design guideline to ensure that the old site fire fighting requirements, in the design of the priority selection of high-pressure water mist as the preferred equipment for fire extinguishing. Cart-type high-pressure water mist device, shown in Figure 10, its technical parameters include: droplet size Dv0.99 <400μm (based on ISO9276-2 standard), working pressure ≥ 10MPa, the effective spray distance ≥ 15m, can be realized within 30s of class A fire rapid fire control (thermal radiation flux attenuation rate of > 90%). Movable high-pressure water mist has the appearance of ancient and elegant, that is, not to install piping fittings do not destroy the structure of cultural relics does not affect the layout of ancient buildings. The equipment adopts modular design, the installation process without pre-buried pipeline, to avoid structural intervention on the historical building body (disturbance factor η <0.01). The operation interface meets the requirements of ENISO13849 safety integrity level SIL2, and is equipped with a dual redundant control system to ensure reliable deployment in the complex spatial environment of heritage buildings. Movable high-pressure water mist is special fire-fighting equipment for cultural relics buildings in recent years, featuring strong fire-fighting capability, small water loss, long spraying time, long spraying distance, easy operation and so on.

Figure 10 Trolley-Type Movable High-Pressure Water Mist Object Picture

3.2.2Fire extinguisher setup

The protection zone of the old site belongs to the national key cultural relics protection unit, because of the consideration of keeping the original appearance of the cultural relics building as far as possible, because the fire fighting water source can not meet the requirements, do not carry out the fire hydrant system, fire fighting water cannons and automatic sprinkler system setup. In view of the characteristics of the old site, fire extinguishers are set up in the building, and in the early stage of fire, fire extinguishers are used to put out the fire, and when the fire is large, firefighters can directly use high-pressure water mist devices to extinguish the fire.

By establishing the fire risk evaluation model ($FRI=\Sigma Wi \times Fi$, weight Wi is determined by AHP method), three major high-risk elements are identified: (1) the proportion of wooden components is >62% (moisture content ω=17.3%); (2) the combustible load density q=35kg/m²; and (3) the peak of the daytime personnel load is 2.3 people/m². According to Design Code for the Configuration of Fire Extinguishers in Buildings GB50140-2005, the old site belongs to the fire of solid material, and dry powder fire extinguishers are configured according to the serious danger level of Class A fire. Cultural relics building indoor selection of 5kg portable fire extinguishers, single fire extinguisher minimum configuration level is not less than 3A, the maximum protection distance is 15m, the maximum protection area of the unit extinguishing level is 50m2 / A; Class A fire places of fire extinguishers maximum protection distance and the configuration of fire extinguishers reference table should be determined in accordance with Table 3 and Table 4[2]. Indoor fire extinguisher box is shown in Figure 11.

Figure 11 Indoor Fire Extinguisher Box Physical Picture

Table 3 Reference Table for Maximum Protective Distances for Fire Extinguishers in Class A Fire Places

Hazard Class Fire extinguisher type	Portable fire extinguishers	Trolley fire extinguishers
critical risk level	15	30
medium risk	20	40
Slightly hazardous	25	50

Table 4 Fire Extinguisher Configuration Reference Table

Hazard class	Critical risk level	Medium risk	Slightly hazardous
Minimum configuration of single fire extinguisher fire extinguishing level	3A	2A	1A
Maximum protection area per unit of fire suppression level (m2/A)	50	75	100

4 TECHNICAL MEASURES FOR THE PROTECTION OF HERITAGE BUILDINGS

4.1Profiled Pipe Laying Process

When the pipeline is laid openly on the wall, wooden beams, wooden eaves, it should be fixed by selecting accessories such as hoops and clips.
(1) When the number and quality of wires and pipes are large, it is appropriate to fix them with brackets or metal wiring channels, and the structural load of the building at the load-bearing position should be calibrated so as to avoid causing damage to the building structure.
(2) The pipeline should be sealed with non-combustible materials when crossing the wall, and the pipeline should be placed in a relatively hidden and safe part, and effective and reversible protection measures should be taken for the contacted cultural relics.
(3) Indoor open pipeline (equipment) should be horizontal and vertical, neatly arranged. Pipes and terminals, elbow midpoint, junction box or junction box, electrical appliances and other edge distance should be fixed within 15cm ~ 50cm.
Based on the reverse engineering technology to establish the building body three-dimensional point cloud model (point spacing ≤ 2mm), the development of non-contact pipe laying system：
(1) The open-laying pipeline adopts 6061-T6 magnesium-aluminum alloy clamp (modulus of elasticity E=68.9GPa), the spacing is calculated according to Euler-Bernoulli beam theory (deflection limit f/L≤1/500), and the single-point load is ≤1.5kg (in accordance with EN 1995-1-1 standard).
(2) Silicone fireproof sealing system (UL 2079 Class 125) with coefficient of expansion $\alpha=5.5\times10^{-6}$/°C is set up at the part crossing the wall, and thermal deformation ΔL=0.12mm/m-°C.

4.2 Process Points of Equipment Installation

(1) Before the construction and installation of smoke detectors, sound and light alarms, manual alarm buttons, signal terminal boxes and other equipment, develop a differentiated installation program. With the assistance of heritage management personnel, according to the classification of building component levels, prohibit the construction and installation of complex structures in the structure;
(2) Front-end alarm equipment should be installed by means of hoop or clamp fixing, and the hoop should be lined with rubber pads to prevent the hoop from damaging the building components;
(3) equipment installation should not produce adverse visual impact on heritage buildings, accurate measurement, to be installed correctly to avoid damage to heritage buildings.

5 CONCLUSION

As a historical treasure carrying national memory and civilization genes, the uniqueness of its non-renewability and cultural value determines the extreme importance of fire prevention and control work. Under the background of rapid development of modern fire fighting technology, how to realize the dialectical unity of cultural relics protection and fire prevention and control has become the core proposition in the field of fire fighting engineering. This study through the systematic investigation and intelligent fire system construction, explored the "prevention - inhibition - fighting" trinity of prevention and control path, verified the applicability of high-pressure water spray, profiling pipeline laying and other technologies for the design of cultural relics building fire protection provides both scientific and operable solutions.
In the current practice of fire protection of cultural relics buildings, there is a general tendency of "technology transplantation", that is, the simple application of modern building fire codes, ignoring the vulnerability of the cultural relics and the need for protection of historical features. Such practices can achieve fire fighting, but easily lead to structural damage, material deterioration and other secondary risks, in essence, the fire fighting goal and heritage protection goal of short-sighted behavior. Therefore, it is necessary to establish the "minimum intervention, maximum compatibility" as the principle of cultural relics fire technology paradigm, through the material compatibility research, non-intrusive equipment research and development and the construction of dynamic risk assessment model, the formation of cultural relics of the protection of the body of the priority of the fire technology system.
In the future, the fire protection design of cultural relic buildings should focus on three major directions: 1. deepen multidisciplinary cross research, integrate architectural heritage protection science, fire dynamics and intelligent sensing technology, and develop special fire protection equipments for cultural relics; 2. improve the standard system, formulate differentiated fire protection technology guidelines for cultural relic buildings, and refine the technical requirements of fire resistance enhancement of wooden structures and hidden system integration; 3. promote the application of intelligent fire protection platform, relying on the digital twin and IoT technology. Digital twin and Internet of Things technology to realize the full-cycle closed-loop management of fire risk. Only by treating historical relics with reverence and breaking through technical bottlenecks with innovative thinking can we truly realize the ultimate goal of "protecting cultural relics by eliminating them, and transmitting cultural heritage by technology".

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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