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Research on the Influence of Polyacrylonitrile Precursor on the Properties of Carbon Fibers and Pultruded Composite Materials

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Abstract: Polyacrylonitrile (PAN) precursor is a core precursor for the preparation of high-performance carbon fibers. Its unique chemical structure and physical properties directly contributes to the microstructure and mechanical properties of carbon fibers, and therefore affect the overall performance of pultruded composites. This study systematically investigated the influence of PAN precursor properties on the degree of graphitization, surface morphology and mechanical properties of carbon fibers by regulating the molecular weight distribution, stretching ratio and impurity content of PAN precursor, and analyzed the mechanism of action of carbon fiber properties on the interfacial bonding strength and tensile/bending properties of composites in combination with the pultrusion process. The results showed that when the filament stretchability was increased to 4.5 times, the axial orientation of carbon fibers increased by 18% and the tensile strength reached 520 MPa; Filaments with impurity content below 0.3% increase carbon fiber yield by 5.2% and interlaminar shear strength of composites by 23%. This study provides a theoretical basis for raw material screening and process optimization of high-performance carbon fibers and their composites.

Keywords: Polyacrylonitrile precursor; Carbon fiber; Pultrusion; Composites; Performance effects

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1. Introduction

Carbon fiber is highly resistant to corrosion and has high strength but low density. Due to its advantages and characteristics, carbon fiber is now widely used as a key structural material in aerospace, new energy equipment and other fields [1]. Among them, PAN -based carbon fibers have a relatively high global output, occupying 90% of the market [2].

In the manufacturing process, the primary factor determining its quality was the performance of the precursor, such as the impurity content and orientation of the precursor, which would affect the degree of graphitization and defect distribution of the carbon fiber to a certain extent [3]. As for the preparation of carbon fiber composites, the pultrusion process has stood out due to its own advantages, such as the ability to achieve continuous production and high fiber volume fraction (65–75%), and has now developed into an important technology for the preparation of carbon fiber materials [4].

However, there is not enough study in the industry on the correlation between the properties of the precursor and the properties of pultruded composites, especially the mechanism by which the microstructure of the precursor affects the interfacial bonding behavior of the composites [5]. Hence, this paper takes different specifications of PAN precursor as the research object, attempts to explore the influence of key performance indicators of precursor on the structure and performance of carbon fiber by using the control variable method, and also constructs a performance transfer model of "precursor - carbon fiber - composite" in combination with the pultrusion forming process. The primary aim is to provide more theoretical support for the selection of raw materials and the optimization of processes for high-performance composites.

2. Materials and methods

2.1. Experimental materials

Three different specifications of PAN precursor (A, B, C) were selected, and their basic properties are shown in **Table 1**.

Table 1. Basic performance parameters of PAN precursor

Filament number	Average molecular weight ($\times 10^4$)	Molecular weight distribution (Mw/Mn)	Stretching ratio	Impurity content (%)	Monofilament diameter (μm)
A	15	2.1	3.0	0.5	18 ± 2
B	18	1.8	4.5	0.3	16 ± 1
C	22	2.5	2.0	0.8	20 ± 3

Note: The impurity content mainly includes metal ions, undissolved polymer particles, etc.

2.2. Carbon fiber preparation process

Carbon fiber is produced by pre-oxidation (air atmosphere, 220–280 °C, heating rate 2 °C/min, residence time 90 mins) and carbonization (nitrogen atmosphere, 1200 °C, residence time 30 mins) of the precursor [6]. The pre-oxidation stage focused on controlling the degree of oxidation (10–12% oxygen content), while the carbonization stage controlled the structural evolution by adjusting the rate of heating (5–10 °C/min).

2.3. Preparation of pultruded composite materials

The epoxy resin (E-51)/methyltetrahydrophthalic anhydride (curing agent, mass ratio 100:80), with 3% silane coupling agent (KH-550) was added in the resin system [7]. After the carbon fibers were impregnated with resin in an impregnation tank, they were cured and formed through a heated mold (temperature gradient: 80 °C→ 120 °C→ 160 °C), with a traction speed of 1.5 m/min and a fiber volume fraction of approximately 65% [8]. The sizes of the prepared composite specimens were: tensile specimens (250 × 25 × 3 mm), bending specimens (80 × 10 × 3 mm), interlaminar shear specimens (40 × 10 × 3mm).

2.4. Testing and characterization

2.4.1. Carbon fiber performance testing

The degree of graphitization was analyzed by X-ray diffraction (XRD, Cu Kα radiation, λ = 0.154 nm), and the (002) interplanar spacing (d_{002}) and microcrystalline size (Lc) were calculated; The surface morphology was observed by scanning electron microscopy (SEM, acceleration voltage 5kV); The tensile strength of the filaments was measured using an Instron5948 microforce tester with a gauge length of 20 mm and a tensile rate of 1 mm/min, with 50 filaments tested in each group with the average value recorded [9].

2.4.2. Composite material performance test

Tensile and flexural strength were tested in accordance with GB/T3354-2014 and GB/T3356-2014 standards at a loading rate of 2 mm/min; Interlayer shear strength was tested using the short beam shear method (GB/T3357-2014), with a span of 20 mm and a loading rate of 1 mm/min; Interfacial bonding performance was analyzed by observing the fracture morphology via SEM.

3. Results

3.1. The effects of PAN precursor properties on carbon fiber structures

3.1.1. The effect of stretching ratio on carbon fiber orientation

The stretching ratio directly affects the orientation degree of the precursor molecular chains [10]. **Figure 1** shows the XRD patterns of carbon fibers prepared from filaments with different stretching ratios. As the stretch ratio increased from 2.0 (precursor C) to 4.5 (precursor B), the intensity of the diffraction peak (002) significantly increased and the half-height width narrowed, indicating an improvement in the orientation of the graphite microcrystals along the fiber axis. The Lc value of the carbon fiber prepared from precursor B was 21.5 nm, which was 21% higher than that from precursor C (17.8 nm), and d_{002} decreased from 0.342 nm to 0.338 nm, indicating an increase in graphitization.

The stretching ratio directly affected the orientation degree of the precursor molecular chains [10].

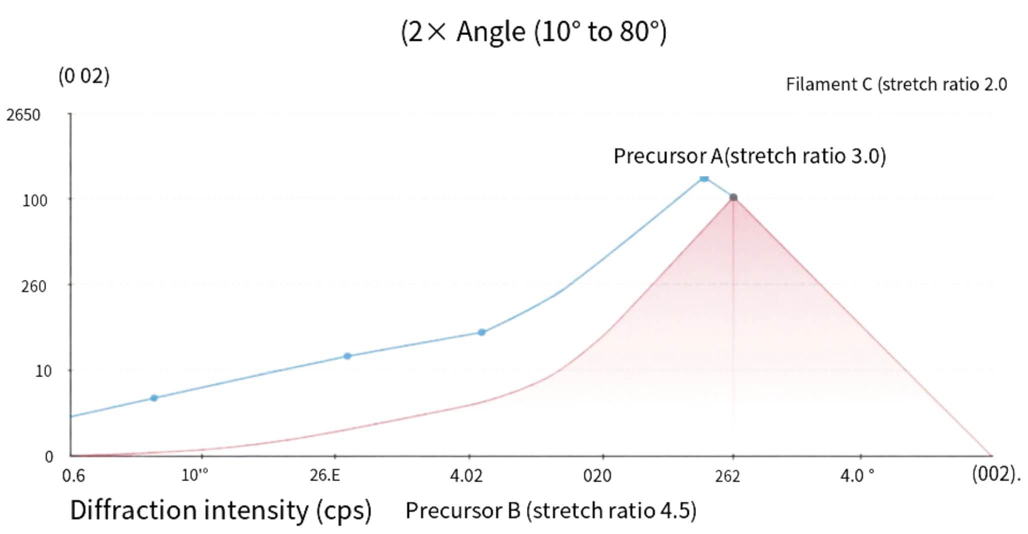

Figure 1. XRD patterns of carbon fibers prepared from filaments with different stretching ratios.

3.1.2. The effect of impurity content on carbon fiber defects

Impurities in the precursor (such as metal ions) can catalyze the cracking of graphite sheets during the carbonization process, resulting in structural defects [12]. **Figure 2** shows the SEM images of carbon fibers prepared from precursor A (0.5% impurity) and precursor B (0.3% impurity). There are obvious longitudinal grooves and protrusions on the surface of precursor A carbon fiber, while the surface of precursor B carbon fiber is smooth with grooves less than 2 μm deep. Energy spectrum analysis showed that the Fe content in precursor A carbon fiber was 85 ppm, significantly higher than 32 ppm in precursor B. Metal impurities act as catalysts for REDOX reactions, intensifying the intense exothermic process during the pre-oxidation stage, resulting in microcracks within the fibers and surface defects after carbonization.

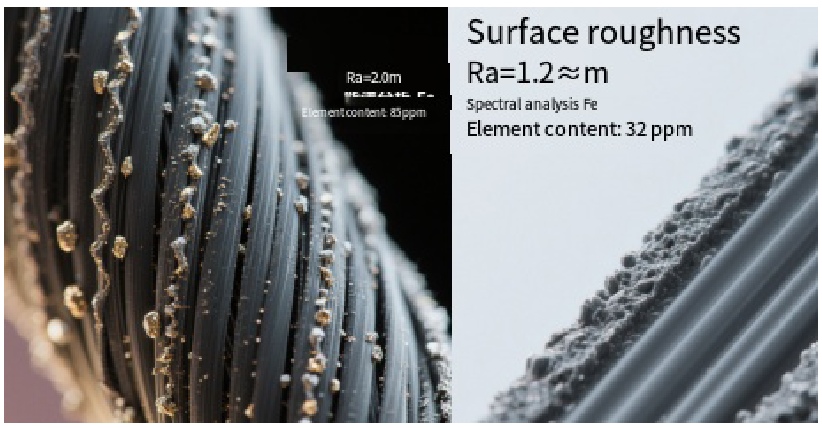

Figure 2. SEM images of the surface of carbon fibers prepared from filaments with different impurity contents.

3.2. The effect of PAN precursor properties on the mechanical properties of carbon fibers

The data on the mechanical properties of carbon fibers prepared with different precursor materials was presented in **Table 2**. The carbon fiber tensile strength of precursor B (high stretch ratio, low impurities) reached 520 MPa, and the elastic modulus was 23.5 GPa, which were 48% and 31% higher, respectively, than that of precursor C (low stretch ratio, high impurities). This difference is mainly due to two aspects: (1) The high elongation ratio improves the orientation of the molecular chain and reduces the stress concentration points; (2) Low impurity content inhibits the formation of defects during carbonization. It is notable that the molecular weight of precursor A is higher (22×10^4), but its mechanical properties are lower than those of precursor B, indicating that the broadening of the molecular weight distribution (Mw/Mn = 2.5) led to uneven molecular chain entanglement and local overheating degradation during pre-oxidation, reducing the density of the carbon fiber [13].

Table 2. Comparison of mechanical properties of carbon fibers

Filament number	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation at break (%)	Yield (%)
A	410 ± 15	20.1 ± 1.2	3.2 ± 0.3	48.5
B	520 ± 20	23.5 ± 1.5	3.8 ± 0.4	53.7
C	350 ± 12	17.9 ± 1.0	2.8 ± 0.2	43.2

3.3. The influence of carbon fiber properties on the interfacial bonding of pultruded composites

3.3.1 The influence of surface morphology on interfacial shear strength

The groove structure on the surface of carbon fibers enhance mechanical meshing with the resin [14]. **Figure 3** shows the SEM images of the fracture surfaces of composite materials prepared with different filaments. The surface grooves of precursor B carbon fiber were uniform, the embedding depth of the resin matrix is about 5 μm, and the fracture shows a large number of resin tear marks, indicating that the interfacial bonding is mainly the combined effect of chemical adsorption and mechanical locking; In contrast, the surface of precursor C carbon fiber is rough but the grooves are irregular, and cavities after fiber extraction can be seen at the fracture. The interfacial shear strength is only 32.5 MPa, which is 23% lower than that of precursor B (42.1 MPa). This suggests that a moderate surface roughness (such as Ra = 1.2 μm for precursor B) was beneficial for improving interfacial bonding, while excessive defects (such as Ra = 2.3 μm for precursor C) was shown to cause a stress concentration and reduce interfacial compatibility.

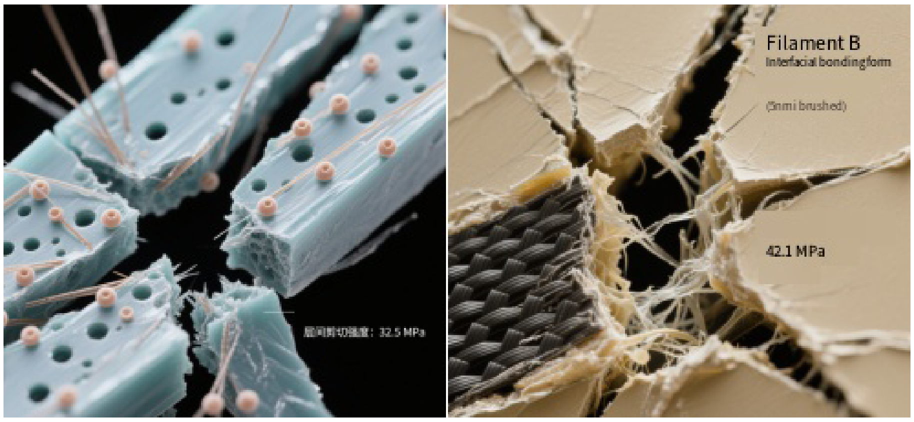

Figure 3. SEM image of the fracture surface of the composite.

3.3.2. The effect of oxidation degree on the adsorption of coupling agent

Controlling the content of oxygen-containing functional groups (such as hydroxyl and carboxyl groups) on the carbon fiber surface during the pre-oxidation stage can enhance the chemical bond interaction of the coupling agent [15]. **Figure 4** shows that the O/C atomic ratio in the XPS profile of precursor B carbon fiber is 0.18, which is higher than 0.12 for precursor A, indicating a better degree of surface oxidation. The silane coupling agent forms hydrogen bonds with the carbon fiber surface through hydroxyl groups, and after curing, it generates Si-O-C chemical bonds, which increase the interlamellar shear strength of the composite. Infrared spectroscopy analysis showed that the absorption peak intensity of the precursor B composite at 1020 cm^{-1} (Si-O-C stretching vibration) was 35% higher than that of the precursor A, confirming the enhanced inter-interface chemical bonding.

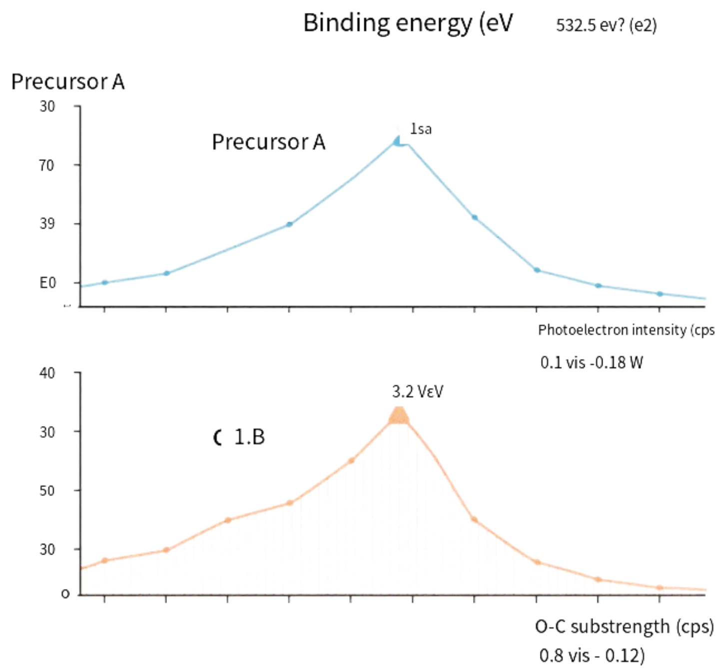

Figure 4. XPS spectra of carbon fiber surface.

3.4. Analysis of mechanical properties of pultruded composites

Table 3 shows the data of mechanical properties of composites with different precursor systems. Precursor B composites have tensile strength of 1280 MPa, flexural strength of 1120 MPa, and interlaminar shear strength of 42.1 MPa, all significantly superior to other systems. Correlation analysis shows that the tensile strength of carbon fibers is linearly positively correlated with the tensile strength of composites ($R^2 = 0.96$), and the correlation coefficient between interfacial shear strength and interlayer shear strength is 0.92.

Table 3. Mechanical properties of pultruded composites

Filament number	Tensile strength (MPa)	Flexural strength (MPa)	Interlaminar shear strength (MPa)
A	1050 ± 40	910 ± 35	35.8 ± 2.1
B	1280 ± 50	1120 ± 45	42.1 ± 2.5
C	890 ± 30	780 ± 30	32.5 ± 1.8

4. Discussion

In this study, the effects of precursor properties on the structural and mechanical performance of carbon fibers and their composites were investigated. It was observed that increasing the stretching ratio significantly improved the orientation of the carbon fibers, which led to enhanced graphitization and better mechanical properties.

The tensile strength and elastic modulus of precursor B carbon fiber, prepared with a high stretching ratio and low impurity content, were notably higher than those of precursor C. The impurities present in the precursor materials had a detrimental effect on the carbon fiber structure, promoting defects during the carbonization process. This was evident from the SEM analysis, where precursor A, with higher impurity content, showed more surface defects. The relationship between impurity content and fiber quality highlights the importance of controlling impurity levels to reduce defects and improve fiber performance.

Surface morphology also played a critical role in the interfacial bonding between carbon fibers and the resin matrix in the pultruded composites. Moderate surface roughness (Ra = 1.2 μm) was found to optimize the interfacial shear strength, while excessive surface defects could lead to stress concentration and poor bonding. Additionally, controlling the degree of oxidation of the carbon fiber surface during pre-oxidation enhanced the chemical bonding with the coupling agent, further improving the interfacial properties. The overall mechanical properties of the pultruded composites were also heavily influenced by the precursor properties. Composites made from precursor B fibers exhibited superior performance, demonstrating the importance of both fiber orientation and surface treatment in achieving high-quality composite materials.

5. Conclusion

The drawing ratio and impurity content of PAN precursor are key factors affecting the structure and performance of carbon fibers. An increase in the drawing ratio to 4.5 times increases the carbon fiber orientation by 18%, and when the impurity content is below 0.3%, the carbonization yield increases by 5.2% and the defect density decreases.

The surface morphology of carbon fibers and the degree of oxidation significantly affect the interfacial properties of pultruded composites. Moderate surface grooves (Ra = 1.0–1.5μm) and oxygen-containing functional groups (O/C = 0.15–0.20) can increase interlaminar shear strength by more than 20%.

A transfer mechanism of "precursor properties - carbon fiber structure - composite properties" was established: high regularity precursor → low defect carbon fiber → strong inter-interface bonding composite. In actual production, PAN precursor with a narrow molecular weight distribution (Mw/Mn ≤ 2.0), stretching ratio 4.0–5.0, and impurity content < 0.3% is recommended for the preparation of high-performance carbon fibers and pultruded composite materials.

Further research could be conducted on the effects of precursor spinning processes (such as dry-wet spinning parameters) on the microporous structure of carbon fibers, as well as the optimization effect of nano-filler modification on interfacial thermal stress matching to promote the application of carbon fiber composites in extreme environments.

Disclosure statement

The authors declare no conflict of interest.

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Application of Carbon Fiber Composite Materials for Automotive Lightweighting

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Abstract: The automobile industry is the first to form a typical representative of the global industry in modern industry, with the increase of the national emphasis on the environment, the automobile industry was regarded as an important energy consumption and one of the sources of environmental pollution, the policy of energy conservation and emission reduction requirements for the automobile industry are becoming stricter over the years, energy conservation and emission reduction has becomes the main direction of product optimization in the automobile industry in recent years. Due of a series of excellent properties such as light weight and high strength, composite materials have become the main material for the development of lightweight vehicles. With the development of material technology and the update and iteration of manufacturing technology, composite materials are currently popular being adopted in the automotive field.

Keywords: Automobile lightweight; Carbon fiber composite; Application research

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1. Introduction

1.1. Overview of carbon fiber composite materials

As a new type of high-performance material, carbon fiber composite has shown significant application value in many fields by virtue of its unique physical and chemical characteristics [1]. This type of material uses carbon fiber with more than 95% carbon content as reinforcement, combined with resin, metal or ceramic matrix, to form a composite system with high strength and high modulus characteristics. Carbon fiber composites have been widely adopted in aerospace, wind power generation, aircraft manufacturing and other fields [2]. At the same time, with the progress of technology and the change of market demand, this kind of material has gradually expanded to sports and leisure, automobile manufacturing, industrial machinery, rail transportation and medical equipment and other industries.

1.2. The advantages of carbon fiber materials applied to automobiles

In the automotive field, carbon fiber composite material stands out with its unique advantages. Compared to other commonly used materials such as high-strength steel, aluminum alloy, magnesium alloy, titanium alloy and glass fiber composites, carbon fiber composites showed superior performance in several aspects [3]. From the perspective of material properties, carbon fiber composite materials can effectively achieve the goal of lightweight automotive. This feature not only reduces the mass of the vehicle, but also significantly improves the fuel economy and environmental performance. Research data show that when the weight of the vehicle is reduced by 10%, the fuel consumption can be reduced by 6–8%, the exhaust emission is reduced by 5–6%, and the acceleration performance (0100 km/h) is increased by 8–10%, and the braking distance is also shortened by 2 meters to 7 meters.

Safety is one of the most important considerations in the design of modern automobiles, and carbon fiber composites also perform well in this regard. By reducing body mass, the center of gravity of the vehicle can be moved down, which improves the vehicle handling stability and makes the driving process safer and more reliable. In addition, the energy absorption capacity of carbon fiber composites is far superior to that of traditional materials, and the energy absorption effect of carbon fiber composites can be six to seven times that of steel and three to four times that of aluminum, which provides a higher level of safety for passengers.

Comfort, as one of the important indicators to evaluate the performance of automobiles, has also been significantly improved by the application of carbon fiber composite materials. Due to the excellent vibration damping properties of the material, its performance in suppressing noise, vibration and acoustic vibration roughness (NVH) is particularly outstanding. Experimental data show that the traditional light alloy takes 9 seconds to completely stop vibration, while the carbon fiber composite takes only 2 seconds to complete the process [4]. Therefore, cars made up of carbon fiber composite materials has proven to provide a quieter and smoother driving experience during driving.

Reliability is a key parameter to measure the service life of automotive components. Carbon fiber composites have obvious advantages in fatigue strength, and their fatigue resistance can reach 70% to 80% of the tensile strength, which is much higher than the 30–50% of steel and aluminum. This means in practical applications, the carbon fiber composite materials of car parts can still maintain a high performance after long time use, to prolong the life of the vehicle and reduce maintenance costs.

Considering the above characteristics, the application prospect of carbon fiber composite materials in the automotive field is broad. Whether from the perspective of energy saving and emission reduction, or considering driving safety, ride comfort and component reliability, the material has shown unparalleled technical advantages. In the future, with the further reduction of production costs and continuous optimization of technical processes, CFRP is expected to play an even more important role in the automotive industry.

2. Applications of carbon fiber composites in automotive components

2.1. Drive shaft and high-pressure hydrogen storage bottle

Compared with the dry winding technology, the wet winding technology has a significant advantage in cost, which is about 40% lower. In addition, it provides better air tightness, better fiber alignment parallelism, and can effectively reduce fiber wear during production. These advantages have made the wet winding process widely used in many fields, especially in the automotive industry, such as the manufacture of drive shafts and hydrogen storage bottles [5]. The performance of automobile transmission shaft design including shaft bending rigidity, torsional rigidity and critical speed, this is because of its stress distribution is more complex, high demands on the performance of the material. The traditional drive shaft steel material will have poor stability and other ills.

Carbon fiber composite automobile transmission shaft can be a good solution to this problem and effectively improve the performance of the car. Carbon fiber composite materials have high tensile strength, low density, high specific strength, corrosion resistance, high modulus of elasticity and the modulus than the relatively low, the characteristics of the transmission shaft of alternative metal material can better meet the demand of use. In addition, the carbon fiber composite drive shaft not only can reduce weight by 40–50%, such as Toyota 86 carbon fiber transmission shaft and Lamborghini sixth element concept car drive shaft, and has better fatigue resistance and durability.

The wet winding process has also been used to prepare carbon fiber wrapped hydrogen bottles for new energy vehicles. High-pressure hydrogen storage bottles are divided into type I, type II, type III and type IV bottles according to the different liner materials and fiber winding, which are pure steel, steel liner fiber winding, metal (steel and aluminum) liner fiber winding and plastic liner fiber winding bottles [6]. In the technology of vehicle hydrogen storage bottle, the international has been able to produce a large number of 70MPa carbon fiber winding type IV bottle, and the mainstream domestic hydrogen storage bottle is still 35 MPa carbon fiber winding type III bottle, its inner material is aluminum alloy/plastic, the outer coating material is carbon fiber composite material. The research of the American Automotive Research Council shows that when the production scale of high-pressure hydrogen storage bottles increases from 10,000 sets to 500,000 sets, the cost will fall by one-fifth. Therefore, with the breakthrough of the domestic carbon fiber winding preparation technology and the expansion of the production scale, the vehicle high-pressure hydrogen storage bottle will certainly bloom in the future.

2.2. Wheel hub and brake disc

The autoclave process is used in the wheel hub forming process of the automobile. The autoclave process has several significant advantages: first, the pressure distribution is uniform; Secondly, the pressure and temperature are uniform and controllable; Then the mold design is simple, high efficiency, suitable for large area complex surface plate, shell, and simple shape plate, rod, tube, block; Finally, the molding process shows its stability and reliability. The use of carbon fiber composite hubs can significantly reduce weight, which helps reduce the wheel's rotational inertia, allowing the car to achieve faster speeds during starting, braking and steering [7]. Ford's new generation Mustang Shelby GT350R, for example, features such carbon fiber wheels. Similarly, Swedish supercar maker Koenisag uses carbon fiber for the rest of the entire hub in its Agera model, except for the tire valve nozzles. This design not only reduces weight, but also ensures structural sturdiness and safety.

In addition, the automobile brake disc also uses the autocompression tank process, the traditional brake liner mainly uses asbestos material, which will appear heat decay phenomenon under the high temperature generated by high-speed friction, thus producing asbestos dust, which is harmful to health. Carbon fiber composite material has high specific strength, excellent heat decay resistance and excellent wear resistance and heat resistance, which can completely replace asbestos in automobile brake system. The carbon fiber brake disc can withstand the high temperature of 2500 °C, can reduce the speed from 300 km/h to 50 km/h within 50 m, and help to reduce the weight of the automobile chassis, improve the flexibility of the steering wheel, and reduce the jitter phenomenon above the body suspension, and ensure personal safety.

2.3. Roof structure and leaf spring

Carbon fiber composite materials have been widely used in automotive parts, such as battery box, support column, roof structure and leaf spring and other key parts are used in such materials. In the manufacturing process, the high-pressure resin transfer molding process (HRRTM) is widely used. HRRTM is based on the traditional resin transfer molding process. The core of HRRTM is to inject a mixture of low viscosity resin and curing agent into the closed mold cavity under high pressure to achieve full impregnation of the fiber. At the same time, the curing process is completed by precise control of temperature and pressure, so as to form high-quality parts. Compared with autoclave molding process, HRRTM process has significant advantages of low cost, short cycle time and mass production [8].

In automobile suspension system, leaf spring, as an important part, is usually made of composite materials with high strength, large energy storage and corrosion resistance. This kind of material not only has good vibration attenuation performance, but also can achieve elastic bending, so it shows unique advantages in automobile design. There are various manufacturing processes for composite leaf springs, including winding model forming, high pressure resin transfer model forming, and SMC pultrusion forming methods. Among them, SMC pultrusion process takes the traction force as the driving force, and cures the fiber belt or fiber cloth through the mold to realize the continuous production of composite leaf springs with different section shapes. In the winding model forming process, the prepreg fiber is wound on the surface of the die, and the final product is formed through the die closing and curing steps.

With the development of lightweight automobile, mass production of composite leaf springs has become an inevitable demand. At this time, the high-pressure resin transfer model molding process has become an ideal choice to meet this demand because of its high degree of automation and fast production efficiency. Compared with the traditional leaf spring, the composite leaf spring shows obvious advantages in performance. Its high elasticity can effectively improve the comfort of vehicle driving; while having stronger fatigue resistance, fatigue life can reach 8 - 10 times of ordinary leaf spring. In addition, the composite plate spring has excellent performance in vibration damping, which can absorb vibration energy through its own damping characteristics, so as to ensure the smoothness of the vehicle [9]. The composite leaf spring consists of large number of independent fibers, which together form a statically uncertain system. When some fibers are broken, the load can be automatically transferred to other fibers to avoid the bearing capacity of the suspension structure being affected, so as to ensure the safety and stability of the car driving.

3. Application status of carbon fiber composite materials in automobile lightweight

3.1. The main challenges faced by the industrialization of carbon fiber composite materials

There were many constraints in the industrialization process of carbon fiber composite (CFRP). From the cost point of view, reducing the price of carbon fiber is the key to improve its market competitiveness. The Rock Mountain Research Institute has conducted an in-depth study on the application of carbon fiber in the automotive industry. The results indicated that when the price of carbon fiber unit drops below 16.5 US dollars /kg, it will show stronger competitiveness compared with steel. One of the effective ways to achieve this goal is to use low-cost large bundle carbon fiber, whose price is only 50% - 60% of small bundle carbon fiber [10]. At the manufacturing technology level, the existing production process of carbon fiber composites is generally inefficient, which is difficult to match the demand of the modern automobile industry for high production pace. Therefore, the development of new processing technology to shorten the molding cycle has become an important issue to be solved urgently. By improving the process flow, the production efficiency would be significantly improved. Hence, to better meet the requirements of large-scale quantitative production. In addition, it is also crucial to ensure the stability of CFRP performance and the consistency of component quality.

The quality of composite products is affected by the characteristics of raw materials and various aspects of the process. In order to achieve high quality consistency, it is necessary to strictly control the curing process, optimize the process parameters, and introduce a highly automated production method to ensure a high degree of repeatability of the process. These measures can effectively reduce the variability, thus ensuring that the final product has a stable and reliable performance.

3.2. Progress in the application of carbon fiber composite materials in automobiles

Due to its excellent lightweight characteristics and mechanical properties, carbon fiber composites have shown a wide range of application prospects in the field of automotive parts. In recent years, CFRP has been gradually applied to the manufacturing of automotive core components, especially in the body and chassis. For example, GM's ultra-light concept car has achieved 68% weight reduction by using carbon fiber for body and chassis. The Subaru WRX STI TS uses a CFRP roof, which reduces weight by 80% compared to a high-strength steel roof. In the braking system, brands such as Porsche AG have put carbon fiber brake discs into use to successfully reduce the vehicle from 300 km/h to 50 km/h in only 50 m distance. Significant progress has also been made in the field of transmission shafts. The Toyota 86 is equipped with a carbon fiber shaft weighing only 5.53 kg, which is 50% lighter than the traditional material. In addition, Japan has recently developed the technology of replacing aluminum alloy with carbon fiber to manufacture compressor impellers, which not only shorter the response lag time, but also achieves 48% weight reduction.

Globally, BMW has become one of the first enterprises to realize the large-scale application of carbon fiber in mass production vehicles, which has promoted the technological innovation of carbon fiber in the automotive field. Through deep cooperation with carbon fiber companies such as SGL and Mitsubishi Rayon, and relying on the production network distributed in three countries and five places, BMW has effectively reduced the manufacturing cost of carbon fiber and laid the foundation for large-scale application. From the i3, i8 to the new 7 Series, BMW continues to explore the path of mass production of carbon fiber body. Each BMW i3 uses about 200,300 kg of carbon fiber composite material, and the weight reduction effect is 250,350 kg, with a total vehicle mass of only 1,224 kg. The lightweight nature of the carbon fiber body significantly improves the vehicle's performance and range, while saving about $1,299 in battery cost. The successful mass production of BMW i3, i8 and the new 7 Series fully demonstrates the feasibility of carbon fiber for mass production applications in the automotive industry. However, given that the cost of carbon fiber is still at a high level, automobile manufacturers need to comprehensively consider the pricing power and market acceptance of vehicles when applying carbon fiber in practice.

Domestic manufacturers are also making breakthroughs in the field of carbon fiber for automotive use. In joint research with the Chinese Academy of Sciences, Chery developed the composite material system, structural part design and rapid prototyping process for the Erize 7 model, and completed the verification and evaluation of the material and structural part performance. This series of innovations has made carbon fiber composite materials widely used in this model, and achieved good lightweight effect and vehicle performance improvement.

4. Conclusion

Overall, the excellent properties exhibited by carbon fiber composites are a key factor driving the growth of the market; sound green and low carbon development mechanisms coupled with awareness of the positive impact of green and light vehicles can directly contribute to the growth of the market. In addition, fuel-efficient vehicles are environmentally friendly, have high driving range, can run on alternative fuels, and use advanced fuel technologies. Hybrid vehicles, battery-powered vehicles, plug-in hybrids, and pneumatic electric vehicles are some of the fuel-efficient vehicles favored by consumers. These light vehicles make heavy use of composite materials, which directly increases the demand for the market during the forecast period. Although the cost reduction of carbon fiber may not happen immediately, the application of carbon fiber in automotive lightweighting will become more economically viable with technological advances, production scale up, application of automation and robotics, development of recycling and reuse technologies, policy and market incentives.

Disclosure statement

The authors declare no conflict of interest.

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A Framework of Information Sharing Platform for Prefabricated Building Supply Chain Based on BIM

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Abstract: In view of the imperfect supply chain management of prefabricated building, inadequate information interaction among the participating subjects, and untimely information updates, the integration and development of BIM technology plus the supply chain of prefabricated building is analyzed, and the problems existing in the current supply chain and the application of BIM technology at various stages are elaborated. By analyzing the structural composition of the prefabricated building supply chain, an information sharing platform framework for prefabricated building supply chain based on BIM was established, which serves as a valuable reference for managing prefabricated building supply chains. BIM technology aligns well with assembly construction, laying a solid foundation for their synergistic development and offering novel research avenues for the prefabricated building supply chain.

Keywords: BIM technology; Supply chain management; Prefabricated building; Information flow

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1. Introduction

Prefabricated buildings revolutionize modern construction with standardized designs and assembly-based methods, boosting efficiency and quality [1, 2]. The Ministry of Housing and Urban-Rural Development's 14th Five-Year Plan emphasizes the advancement of prefabricated construction standards and automation [3]. Despite these benefits, the construction process is complex due to various participants and constraints [4].

Current information technology in construction hinders supply chain efficiency [4]. BIM technology offers a solution for improved information flow, with applications in risk and cost management [5, 6]. However, comprehensive BIM-based supply chain management for prefabricated buildings is lacking. This study developed a BIM-based information-sharing platform for the prefabricated building supply chain, ensuring timely and accurate information exchange [7, 8]. This platform integrates project data, enhancing collaboration and objective achievement for all stakeholders.

2. Related work

2.1. BIM technology

Building Information Modeling (BIM) is a digital standard in the building industry, leveraging 3D models to enhance design, construction, and operation processes [9]. BIM supports collaboration and allows for visual decision-making. It extends beyond 3D with time (BIM4D), cost (BIM5D), sustainability (BIM6D), and facility management (BIM7D) dimensions. Researchers have developed a life-cycle BIM maturity model with guidelines for achieving full BIM integration [10].

2.2. Construction supply chain

Supply chain management research originally centered on manufacturing but expanded to construction in the 1990s with Koskela's work [11]. The construction supply chain broadly encompasses all activities and organizations from project initiation to completion, including maintenance and building lifecycle stages [12]. It is categorized into external and internal chains, with the external chain forming a network around the contractor, connecting various stakeholders through logistics, information, and finance (**Figure 1**).

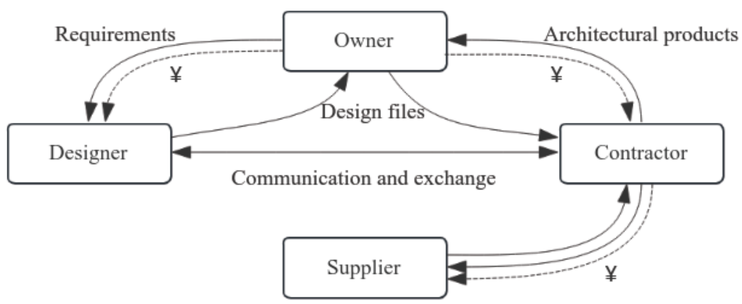

Figure 1. Supply chain of construction industry

The internal supply chain, on the other hand, comprises the various functional departments within a construction company that are related to the construction project. It involves the collaboration of departments such as finance, cost, and technical teams, which are interconnected through logistics, capital flow, and information flow. This network structure enables these departments to work together towards achieving the project's objectives.

2.3. Supply chain management model for prefabricated building

2.3.1. Prefabricated building supply chain analysis

The lifecycle-based prefabricated building supply chain encompasses decision-making, design, production, storage, construction, and maintenance stages. Developers assess projects and establish bidding intentions during the decision stage. Design units integrate BIM and intelligent cloud design, involving manufacturers and construction units. General contractors ensure component constructability and quality, coordinating production and procurement with strict quality control. Storage and transportation use BIM to ensure component integrity. Post-construction, developers handle sales and recycling, aligning with sustainability.

The prefabricated supply chain, distinct from traditional ones (**Figure 2**), features shorter construction cycles, factory production, and on-site assembly. It involves multiple parties with high information sharing and coordination levels.

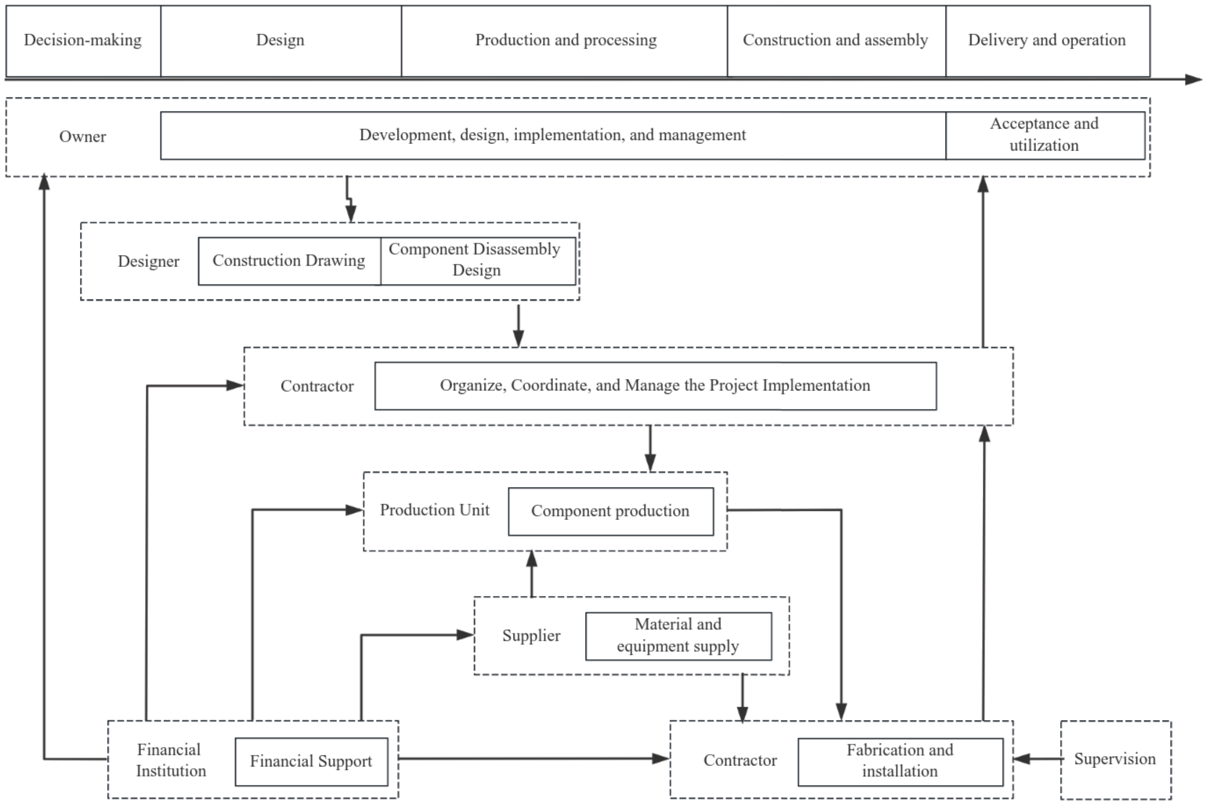

Figure 2. Supply chain of prefabricated building

The flow of information in the supply chain of prefabricated building is a two-way flow that possesses a certain order. As can be seen from **Table 1**, the amount of information required by each participating party is large and the information interaction between the participants is closely linked. Amongst other things, the information flow has the following characteristics:

Table 1. Information flow of relevant parties involved in the supply chain of prefabricated building

Participating parties	Synergistic parties	Information needed	Information submitted
Owners or developers	Designers; Contractors	Overall project planning, documentation contracts, investment and progress control reports, etc.	Project master plans, master investment mandates, owner change and confirmation orders, etc.
Designers	Owners or developers	Project opportunity feasibility studies, design briefs	Preliminary construction documents and construction drawings, information on design changes, etc.
Contractors	Owners; Designers; Prefabricated component manufacturers	Document contracts, construction drawings, design briefs, material and equipment supply schedules, owner's change and confirmation orders, etc.	Progress, quality, cost and other planning statements
Prefabricated component(PC) manufacturers	Designers; Contractors	Construction schedule control plan, material and mould supply plan	PC production completion nodes, component transport plans
Logistics transporters	Designers; Prefabricated component manufacturers	Actual site progress, PC production completion nodes	PC transport planning, storage planning

The supply chain information in construction is vast and diverse, originating from various sources including construction, supervision, supply, production, design, and government entities. It encompasses structural, electrical, and HVAC aspects, as well as management areas like investment, scheduling, environment, risk, contracts, and quality. The information is extensive and varies in format, such as engineering drawings, progress diagrams, and quantity forms, with complex interdependencies and constant updates due to the construction environment and uncertainties.

2.3.2. Current status of the supply chain management model for prefabricated building

The supply chain of prefabricated buildings, encompassing engineering and manufacturing, significantly differs from traditional models. Its multi-stage nature results in complex, dynamic, and intertwined information networks, complicating management. Despite efforts to integrate prefabricated buildings with supply chain management, several issues persist [13].

(1) Inadequate coordination and cooperation among supply chain entities

The prefabricated building supply chain involves owners, constructors, designers, supervisors, and component producers. Each entity plays a crucial role, and issues in any segment can disrupt the entire chain. Effective coordination among these departments remains a critical challenge.

(2) Information asymmetry

With numerous nodes in the supply chain, companies rely on node-specific information for raw material procurement and goal setting. However, limited inter-departmental information exchange leads to discrepancies, exacerbating over time. This asymmetry, especially at the supply chain ends, can have severe repercussions. The complexity of prefabricated building supply chains amplifies this issue, potentially leading to cascading errors.

(3) Improper connection between logistics and construction process

Logistics, influenced by time and space, accumulates errors sequentially. Initial problems impact subsequent stages, disrupting the entire construction process. Factors such as natural disasters, storage requirements, product quality, delivery schedules, casualties, geological conditions, and material delivery timings further complicate this connection.

(4) Contradiction between a single source of information and multiple information needs

Decision-making in prefabricated building supply chains demands extensive information. Multiple actors with high information needs complicate this process. While individuals can gather internal and external data or request it from various nodes, the quality of information varies based on the subject's qualifications, resources, and technical capital. This often fails to meet the diverse information needs of supply chain participants.

2.4. The application of BIM technology in supply chain management of prefabricated building

2.4.1. Information integration of BIM technology in supply chain

BIM technology provides technical support for the integration of information technology in the design, production, transportation, construction, operation, and maintenance stages of prefabricated building. It coordinates the relationship between various subjects and establishes a new cooperation model to ensure the quality of the project to the maximum extent and avoid causing waste of funds, while mobilizing the community to promote the application of prefabricated building [14]. The information sharing platform framework of prefabricated building supply chain based on BIM is depicted in **Figure 3**.

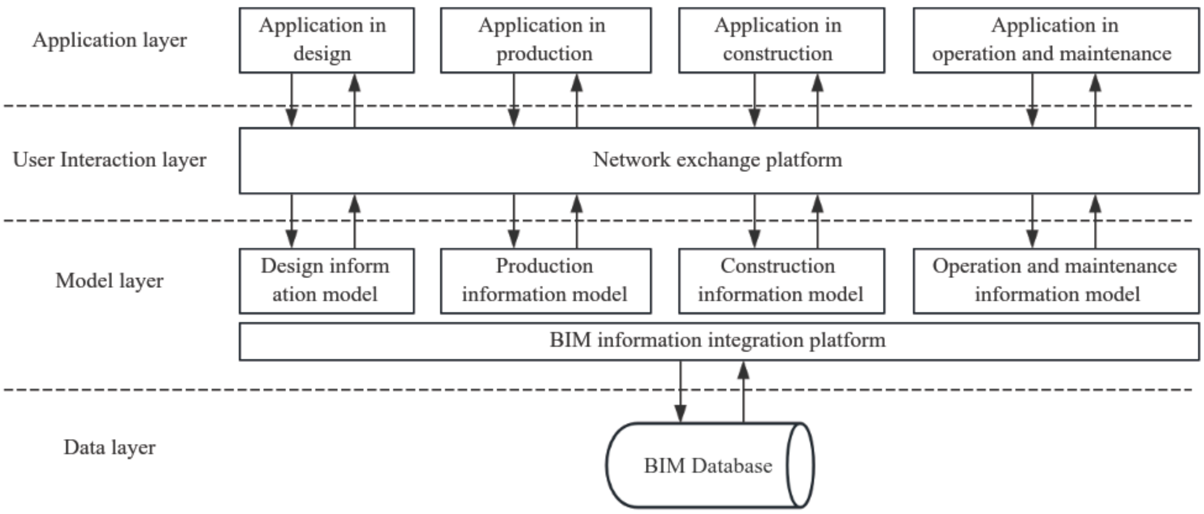

Figure 3. The information sharing platform framework for prefabricated building supply chain based on BIM

The construction supply chain involves vast and intricate information, spanning the entire building project lifecycle from planning to operation. BIM serves as the core, integrating data from various stakeholders (survey, design, construction, etc.) via an interactive platform to manage complex information flows [15]. The following steps and key points can be followed to achieve SCI in BIM:

(1) Define integration goals

Establish clear objectives, such as enhancing efficiency, reducing waste, and optimizing resources. Identify specific BIM data to integrate, like material lists and labor plans.

(2) Select appropriate BIM and supply chain management software

Choose BIM software (e.g., Revit, ArchiCAD) with strong compatibility and supply chain management software (e.g., Oracle, SAP) that integrates seamlessly with BIM [16].

(3) Data standardization and information sharing

Develop unified standards (e.g., IFC) for data exchange. Set up a platform for real-time synchronization of BIM and supply chain data.

(4) Implement integration of BIM model and supply chain software

Use APIs or ODBC to link BIM and supply chain software, enabling automatic import of design data to generate accurate material and labor plans.

(5) Application and optimization of supply chain information

Leverage supply chain software's analytics to analyze BIM data, identify issues, and optimize processes, such as material procurement and inventory management.

(6) Continuous information updates and collaborative work

Ensure real-time updates of the BIM model are reflected in supply chain plans. Utilize the BIM platform for collaborative viewing and decision-making to ensure project smoothness [17].

By adhering to these steps, SCI in BIM enhances supply chain transparency and efficiency, crucial for project success.

2.4.2. Secondary development of Revit

Through Revit's secondary development, tailored functions can be created to facilitate project supply chain participants' access to product information and enhance design data integration. The Revit API supports these developments, allowing integration of external software functions, thereby improving software connectivity and tightening project supply chain management. It also aids in managing model parameters and graphical data [18].

Revit's secondary development is confined to the .NET platform, with the API supporting all NET-based programming languages. These codes are compiled in .NET IDEs, primarily Visual Studio and Sharp Develop. Visual Studio, a widely-used Windows IDE, is ideal for coding, debugging, testing, and deployment, hence Visual Studio Community 2020 was selected for Revit's secondary development.

To begin, set up the development environment in Visual Studio, including essential plugins. The Add-In Manager is crucial for managing other plugins during runtime. Revit Lookup aids in querying element information, assisting developers in optimizing their code [19, 20]. The setup process is illustrated in **Figure 4**.

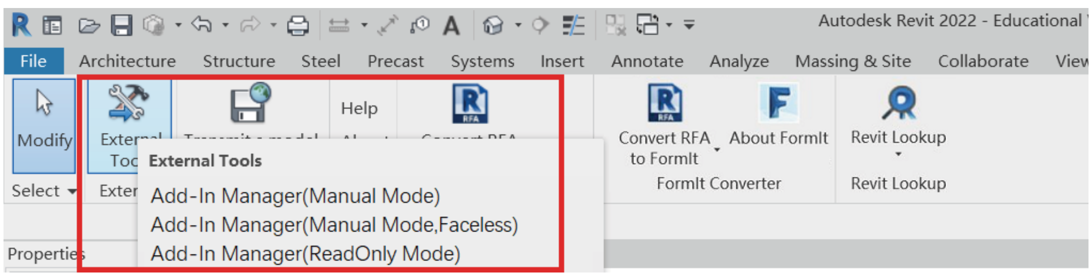

Figure 4. Construction of Revit secondary development environment

After building the development environment, the project can be started, and the business logic code can be written. In terms of software selection, the BIM model of this paper is created in Revit2022 version, and the secondary development of Revit uses Visual Studio Community2020 version, using C # as the development language [21]. The specific Revit secondary development process is shown in **Figure 5**.

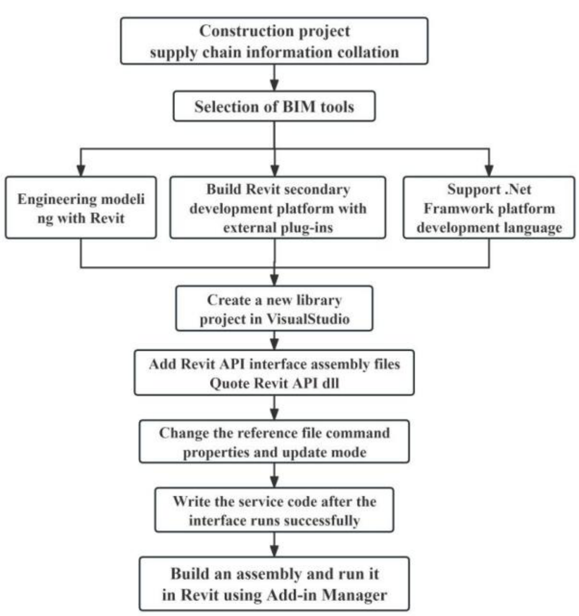

Figure 5. Flow chart of Revit secondary development

In Revit, building information model components encapsulate core data like structure size, material, and function through attributes [22]. Parameters, categorized as instance and type, organize this data effectively: instance parameters apply to specific component instances, while type parameters affect entire component types [23]. Beyond replicating design drawing data, the model integrates component identification, contractor details, and material specifications. As the project progresses, additional data such as construction progress and quality inspections can be incorporated, enhancing the model's data richness. This integration is achieved by setting instance parameters, facilitating comprehensive information management. To simplify participants' access to product information, Revit's secondary development is employed, with relevant code detailed in **Table 2** below:

Table 2. Revit secondary development code

```
Define an external command class
  Set the transaction mode to Manual
  Set the regeneration option to Manual
  Set the journaling mode to NoCommandData
  Define the Execute method for the external command
    Retrieve the application and document object from commandData
    Let app be the commandData.Application
    Let doc be the document of the active UI document

    Get the active UI document and the selection set
    Let uiDoc be the active UI document
    Let selection be the selection set of uiDoc

    Collect the IDs of all selected elements
    Let selectedIds be the element IDs retrieved from selection.GetElementIds()

    Check if any elements are selected
    If (selectedIds.Count == 0)
      Display a message box stating "Please select at least one element."
      Return Result.Failed

    Loop through each element ID in selectedIds
      Let element be the element in doc with the specified ID
      Let info be a string containing element information
      info += "Element info:\n"
      info += "Type name/Named Object: " + element.Name
      info += "\nID: " + id.ToString()
      // The following lines should be adjusted based on the actual element type and available parameters
      info += "\nLength: " + element.GetParameter("Length")
      info += "\nVolume: " + element.GetParameter("Volume")
      info += "\nElevation: " + element.GetParameter("Elevation")

      Display a message box with the element's parameter information
      DisplayMessageBox(info, "Element Parameters")

    Return Result.Succeeded
```

The secondary development of Revit can be achieved by running the program described. Through the family parameter management function of the product information integration platform, project family statistics and component parameters can be obtained. This functionality supports project managers in querying visual design information efficiently. Statistics of family files and family types within Revit project files can be quickly accessed, as illustrated in **Figure 6**. By selecting a component, the design information of key elements such as walls, slabs, beams, and columns can be retrieved promptly, as shown in **Figure 7**. Furthermore, additional design information can be integrated through the extension of family parameters [24].

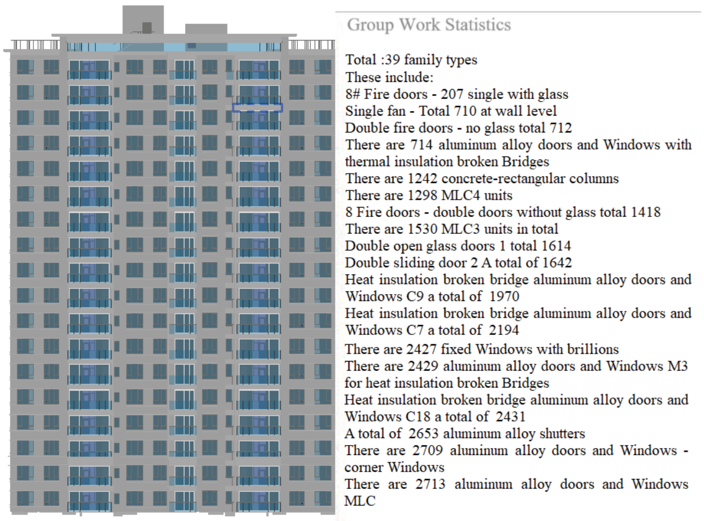

Figure 6. Statistical results of the item families

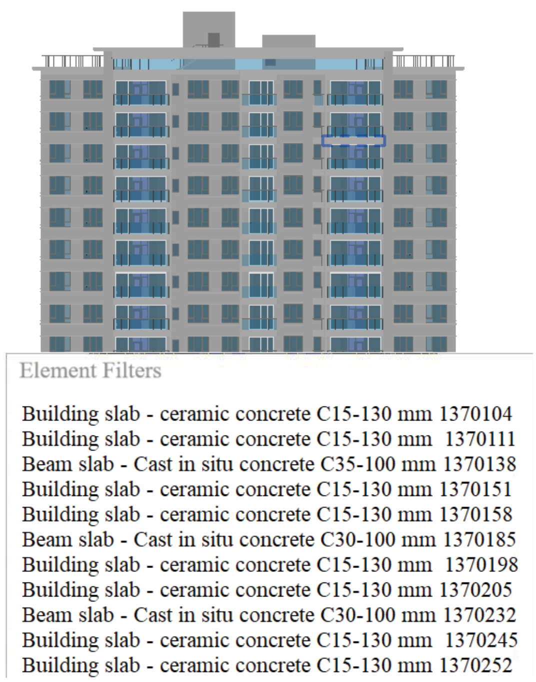

Figure 7. The element information obtained from the element filter

3. Project data management — relational database

The foundation of any information management system and platform is the database, serving as a crucial data repository. Key relational databases today include MySQL, SQL Server, and distributed databases. The prefabricated building project supply chain information integration management platform gathers data from two main sources: structured BIM model information and extensive semi-structured or unstructured data generated during construction [25]. This necessitates the establishment of both a BIM database and an SQL database.

Using BIM model outputs as a foundation and integrating them with SQL Server, the platform consolidates various extended construction-phase information to create a comprehensive data source for project information management [26]. This data source not only underpins the information integration management platform but also supports the development of integrated BIM models [27]. The interaction between the database and Revit involves five key steps, as illustrated in **Figure 8**.

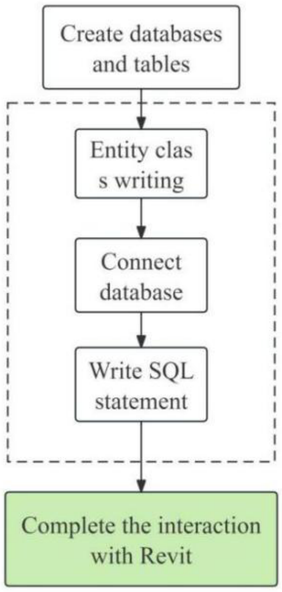

Figure 8. The interaction process

Post-database construction, data sharing and exchange between application software and the database are crucial. Revit's ODBC (Open Database Connectivity) facilitates seamless connections to database management systems. ODBC enables systematic reading and writing of extensive BIM database information, achieving data exchange and sharing [28]. The database framework for the prefabricated building project supply chain information integration management platform, based on BIM, is depicted in **Figure 9**.

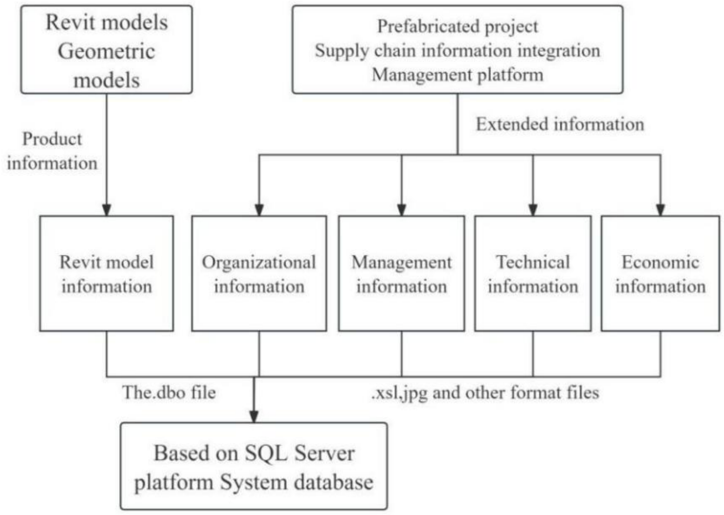

Figure 9. Database construction of project information integration

4. Management platform

4.1. Web platform interface development

To ensure efficient access and utilization of project information, an effective information management system is crucial for seamless sharing and circulation. In web application development, we primarily employ ASP.NET, JSP, and PHP technologies. ASP.NET, a component of Microsoft's .NET framework, facilitates the creation of dynamic, interactive web pages capable of database interaction and personalized content display based on access time and user needs [29]. Its strengths lie in multi-browser compatibility and support for multi-tier development models, which separate logical code into distinct files, thereby clarifying project structure and simplifying later management and maintenance.

This paper proposes a web platform for integrated management of prefabricated building project supply chain information, leveraging the ASP.NET framework. The system architecture is illustrated in **Figure 10**.

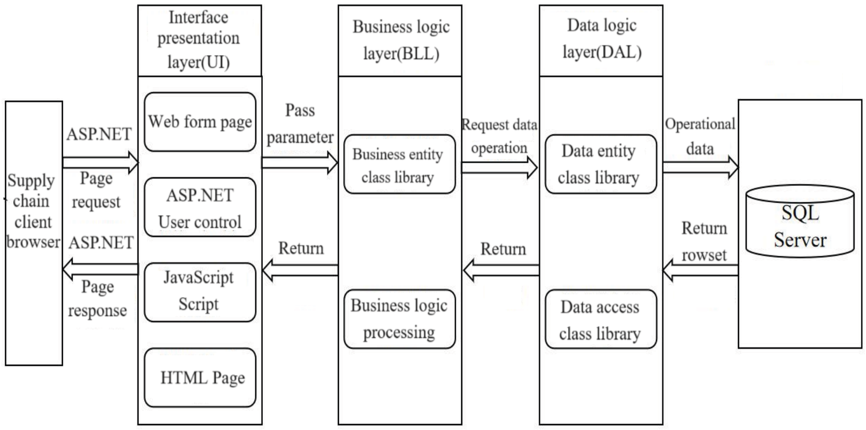

Figure 10. System architecture diagram of the informationintegration management platform

The platform employs a three-layer architecture: the User Interface (UI), Business Logic Layer (BLL), and Data Access Layer (DAL). The DAL handles database interactions, ensuring the BLL accesses necessary data through queries and updates. The BLL processes business logic, performs computations, and validates data, guaranteeing accuracy and integrity, then returns results to the UI [30]. The UI focuses on intuitive design and functionality for user interaction. This architecture is depicted in **Figure 11**.

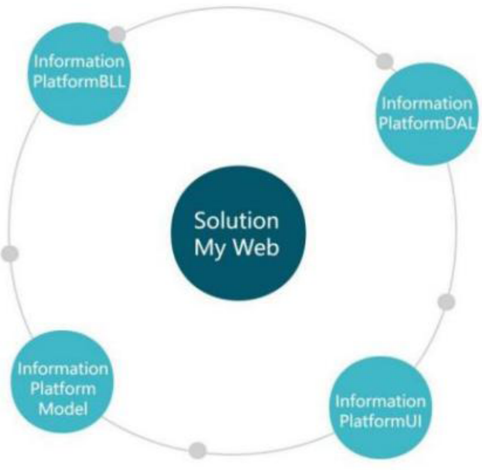

Figure 11. Three-level architecture solution of informationintegration management platform

Figure 12 outlines the technical pathway for integrating supply chain information in prefabricated building projects: Using Revit to build BIM models and integrate product data, enhancing functionality via Revit API for structured information visualization. Leveraging a relational database (e.g., SQL Server) integrates structured and unstructured data. An external database connection facilitates an information management platform, enabling centralized management of project data [31]. All datasets are stored in the relational database, merged with the BIM model for integrated functionality and BIM software applications.

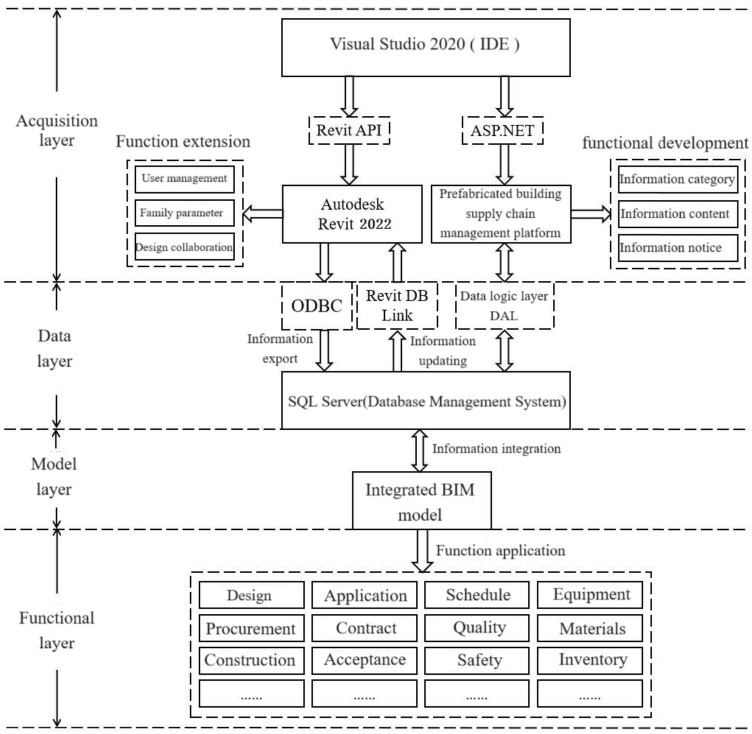

Figure 12. Implementation path of project supply chaininformation integration management technology

5. Conclusion

This article explores the architecture of a BIM-based supply chain information sharing platform for assembly buildings, highlighting its application and value in the industry. Research shows that BIM enhances design efficiency, scheduling, resource optimization, cost control, quality, delivery times, and overall supply chain management in construction. The platform, centered around Revit software, integrates various supply chain information, enabling all participants to access accurate design data for optimized processes. Equipped with data storage, processing, and visualization tools, it aids in managing project uncertainties. This BIM-based architecture introduces an innovative management model, offering significant theoretical and practical benefits.

Currently in the theoretical development stage, the research lacks comprehensive validation. However, future integration of IOT, GIS, VR, and cloud computing promises to enhance supply chain resilience and sustainability, further driving innovation and sustainable development in the construction sector.

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Disclosure statement

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Experimental Design and Material Properties Research of the Reinforced UHPC Columns

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Abstract: Medium shear span ratio reinforced columns are prone to complex failure under seismic action. This paper compares the seismic performance of normal concrete columns and UHPC columns by introducing ultra-high-performance concrete (UHPC). The shear span ratio (2.4-4.4) and axial compression ratio (0.10, 0.36) were used as variables, and the bearing capacity, ductility and failure mode were analyzed through low-cycle reciprocating loading studys. The results showed that UHPC significantly improved the bearing capacity, stiffness and energy dissipation capacity of the column, and suppressed the crushing and spalling of concrete. When the shear span ratio is 2.4 and the axial compression ratio is 0.36, the failure mode of UHPC columns was changed from shear failure to flexural shear failure. Thus this study can become a reference for the seismic design of UHPC columns.

Keywords: Medium shear span ratio; UHPC; Low-cycle reciprocating study; Shear failure; Axial compression ratio

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1. Introduction

The failure modes of medium shear span ratio reinforced UHPC columns under seismic action are complex and lack theoretical prediction methods [1]. UHPC has both high strength (compressive and tensile) and ductility[2], but its seismic performances are yet to be verified. Hence in this paper, one normal concrete column and five UHPC columns were designed with concrete type, axial compression ratio (0.10, 0.36) and shear-span ratio (2.4-4.4) as variables. Low-cycle reciprocating studys were conducted to analyze the horizontal bearing capacity, ductility and failure law, supplemented by concrete and steel bar material property study to provide a theoretical basis for the seismic design of UHPC columns.

1.1. Specimen design and fabrication

Six square short column specimens with a side length of 250 mm were designed, including one ordinary concrete column and five UHPC columns. The variables were concrete type, axial compression ratio (0.10, 0.36), and shear span ratio (2.4, 3.6, 4.4)[3]. The specimens were composed of the column body and end connection blocks, with a protective layer thickness of 30 mm. The longitudinal bars were eight 16 mm HRB400 bars (with a reinforcement ratio of 2.6%), and the stirrups were 8 mm HRB400. The end was set with a stirrup densification zone (densification of 50 mm for specimen 2.4 with a shear span ratio, densification of 100 mm for the rest, with a spacing of 50 mm) to control local stress failure.

1.2. Study setup

The low-cycle reciprocating study setup for the column consists of a reaction beam, a reaction wall, a horizontal actuator and a vertical jack. The specific loading process is as follows: First, a vertical load was applied to the specimen through the vertical jack, and after the vertical load stabilizes, a horizontal reciprocating load was then applied to the specimen through the horizontal actuator. In this study, pushing from left to right was indicated as positive while pulling from right to left was indicated as negative.

1.3. Study point arrangement

The contents measured in the study include the horizontal displacement of the column head, the rotation angles of each column section, the strain of the longitudinal bars and stirrups in the plastic hinge area, the shear deformation of the column, and the distribution of cracks in the column body.

1.3.1. Arrangement of the displacement gauge

Displacement gauge 1 was located at the top column head of the specimen for measuring its horizontal displacement; Displacement gauge 2 was located above the main body of the column and was used to measure the horizontal displacement of each column at different column heights; Displacement gauge 3 was located at the position of the column piers below the specimen and was used to measure its horizontal displacement; Displacement gauge 4 and displacement gauge 5 are fixed on both sides of the column to measure the shear deformation of the specimen, and the vertical displacement gauge were used to measure the bending deformation of the column.

1.3.2. Arrangement of the strain gauge

The strain gauge was attached to the surface of the longitudinal bars and stirrups in the potential plastic hinge area of the specimen. Then, the strain was measured at the corresponding position. The reinforcement strain gauges were evenly arranged along the cross-section.

1.4. Loading regime

The low-cycle reciprocating loading system was designed in accordance with the Code for Seismic Studying of Buildings[4]. The force-displacement hybrid control mode was adopted: the target loads were $0.5F_y$ and $0.75F_y$ before yield, with two cycles at each level; After yield, the target displacement was multiplied $_y$ by Δ, with three cycles per stage. The load was terminated either decreased to 85% of its peak or when the longitudinal bars broke.

2. Concrete material property tests

2.1. Concrete mix ratio

The main components of the ultra-high performance concrete material used in this study include: masterbatch, steel fibers, and water. The masterbatch was mainly composed of sand, cement, silica fume, high-efficiency water reducing agent, ultrafine active powder, quartz powder and additives. The steel fibers were straight steel fibers[6] with a length of 14 mm and a volume content of 2%[7] .

The UHPC mix ratio (by mass) used in this study included: masterbatch: steel fiber: water = 1:0.1:0.115. The main raw materials of Normal concrete (NC) used in this study and their mix ratios (by mass) were as follows: 42.5 grade cement: river sand: crushed stone (coarse aggregate): water: polycarboxylic acid type high performance water reducer = 1:0.7:2.2:0.21:0.1

2.2. Slump and fluidity

UHPC and ordinary concrete were used in the study to measure the slump and fluidity difference in accordance to the Standard study methods for properties of ordinary concrete mixtures (GB/T 50080-2021)[8]. The expansion and slump of the UHPC mixture were continued until it stop expanding or expanding for a duration of 90 seconds. The study measured the expansion of UHPC at 760 mm and the slump at 275 mm. Using the same measurement methods and tools, the slump and fluidity of ordinary concrete were measured, with a fluidity of 470 mm and a slump of 240 mm[9].

2.3. Compressive strength

2.3.1. Cube compressive strength

Concrete compressive strength study were conducted on a 500 t pressure studying machine using the method specified in Standard Study methods for Physical and mechanical properties of concrete (GB/T 50081-2022)[10] , UHPC using 100 × 100 × 100 mm cubic study blocks. For ordinary concrete, 150 × 150 × 150 mm cubic study blocks were used. The loading rate of the studying machine was 1.2 MPa/s - 1.4 MPa/s, and the average value of the material specimens with an average deviation of less than 10% is taken as the measured value of the cubic compressive strength of the material.

Based on **Table 2**, due to the bridging effect of steel fibers, the UHPC cube specimens were remained relatively intact after compression failure, while the ordinary concrete cube specimens were crushed and peeled off at the time of failure, showing a distinct brittle failure pattern.

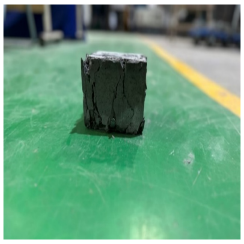
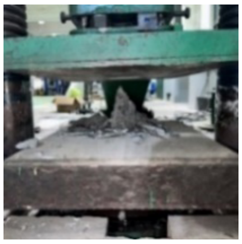
The cube compressive strength of UHPC was measured to be 103.2 MPa, while that of ordinary concrete was 41.2 MPa.

2.3.2. Axial compressive strength

The axial compressive strength of UHPC and ordinary concrete was measured using cylindrical study blocks with diameters of φ100 × 200 mm. The studys were conducted on a 500 t pressure studying machine and loaded using the method specified in GB/ T50081-2022[10]. The compression failure modes of UHPC and ordinary concrete were shown in **Table 1**. The study loading rate was 1.2 MPa/s-1.4MPa/s, and the average value of the material specimens with a deviation of less than 10% has been taken as the measured axial compressive strength of the material.

Due to the use of non-standard specimens, the study results were multiplied by the size conversion factor 0.95 according to the conversion method in Appendix C of GB/ T50081-2022[10] , and the axial compressive strength of UHPC was measured to be 98.0 MPa, and that of ordinary concrete to be 38.4 MPa.

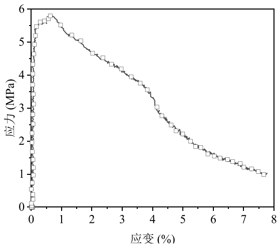
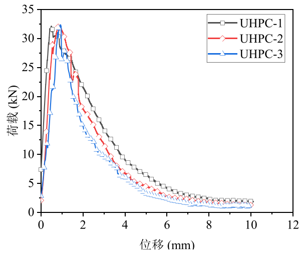
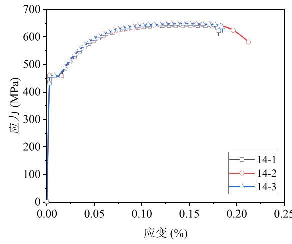
Table 1. Measuring instruments for compressive strength and the final failure mode of specimens

a: UHPC cube failure	b: Ordinary concrete	c: Axial compression failure of UHPC	d: Axial compression failure of ordinary concrete
			

2.4. Tensile strength

Uniaxial tensile tests of UHPC were conducted using “dog bone” shaped specimens (50 mm thick) as stipulated in “Basic Properties and Study Methods[11] of Ultra-High Performance Concrete”. Fiber cloth was pasted in the contraction zone of the middle section of the specimen to ensure the concentration of the failure location, and 50 t universal studying machine was used for loading. Pre-pull (15%-20% of the failure load) and monitor the strain gauge data before the study, and realign when the eccentricity is greater than 15%. The formal loading rate is 0.2 mm/min, and strain gauges (pre-crack strain) and displacement gauges (post-crack displacement) are arranged on the specimen surface. The termination condition of the study is: tensile stress < 30% tensile strength, tensile strain $\geq 1 \times 10^{-2}$ or specimen breakage.

Table 2. Stress-strain curves at the final failure of the specimen under tensile and flexural conditions

a: Typical stress-strain curve under axial tension of UHPC	b: Load-displacement curve of the UHPC four-point bending study for flexural strength	c: Stress-strain curve of reinforcing bars with yield platforms
		

The study shows that the specimen was initially in the elastic phase, then crack sign was appeared rapidly and expanded at their weak points, and the steel fibers was gradually pulled out or break after the concrete breaks. Observation of the fracture section of the “dog bone” specimen shows that all the steel fibers are pulled out or broken, indicating the characteristic of ductility failure.

Taking the typical stress-strain curves obtained from the axial tensile study of UHPC as shown in **Table 2**, it was found that the stress-strain relationship was linear in the early stage of axial tensile of UHPC. After the specimen cracked, the tensile strength of UHPC increased due to the effect of steel fibers. With the complete pull-out and breakage of steel fibers, the specimen eventually failed. The axial tensile strength of UHPC was taken as 5.5 MPa, which is the average of the three specimens.

2.5. Flexural strength

The flexural strength of UHPC was measured using 100 × 100 × 400 mm prismatic study blocks. The study was conducted on the SANS microcomputer-controlled electro-hydraulic servo universal studying machine and loaded using the method specified in GB/T 50081-2022[10]. Before the study, the loading points and support positions were marked on the surface of the specimen. The specimen was located at left and right as well as front and back centered on the support, and the position of the upper loading frame was adjusted before loading. The specimen was loaded continuously and evenly. After the initial crack, the load was loaded 30% lower from the maximum load to fulfill our objective.

The phenomenon of the UHPC flexural study was similar to that of the axial tensile study. In the later stage of the elastic section of the force-displacement curve, cracks in the middle of the concrete was developed rapidly resulting to fracture; Then the steel fibers were gradually pulled out or broke, accompanied by a “sizzling” sound and debris falling. The load-displacement curves were measured for the UHPC specimens, where result was shown in **Table 2**. It was observed that in the early stage of loading, the force on the specimen and its displacement presented a linear relationship. After the concrete cracked, the loading force on the specimen decreased rapidly. Then, due to the effect of the steel fibers at the crack, several ascending sections with unequal peaks appeared on the load-displacement curve, resulting the “jagged” curve. Finally, all the steel fibers at the concrete crack were pulled out and disconnected. The specimen was completely destroyed.

2.6. Elastic Modulus

The elastic modulus of UHPC was measured using prismatic study blocks of 100 × 100 × 300 mm. Vertical strain gauges were attached to the left and right sides of the specimen and displacement gauges were installed to measure the compressive deformation of the specimen before and after the study. The study was conducted on a 500 t testing machine, and the loading[12] was carried out using the method based on GB/ T50081-2019[4]. The specimens were neutralized and preloaded twice before formal loading to minimize the impact of asymmetry and non-uniformity on the specimens. The loading rate was 1.2 MPa/s-1.4 MPa/s. The elastic modulus of UHPC was measured at 43.0 GPa.

2.7. Poisson’s ratio

The Poisson’s ratio of UHPC was measured using prismatic blocks of 100 × 100 × 300 mm. To measuring the horizontal and vertical strength, both strain was attached to the left and right sides of the specimen, respectively. After the specimen was positioned centered, it is initially loaded to 0.5 F_0 and held for 60 seconds, then loaded to one-third of the ultimate load F_a and held for 60 seconds. The operations was repeated twice as preloading. Then, reduce to F_0 and hold for 60 seconds and record the strain gauge data. Then, load to F_a again and hold for 60 seconds and record the strain gauge data. The average Poisson’s ratio test results of UHPC were 0.2.

3. Results

All of the reinforcing bars used in this study was HRB400 bars, which were further classified into four types according to their diameters: 8 mm (used as column stirrups), 14 mm (used as column piers stirrups), 16 mm (used as column longitudinal bars), and 20 mm (used as column piers longitudinal bars)[13].

To determine the material properties of the bars, three 400 mm specimens of each type of bar were cut and fixed on a 30 t universal studying machine, in accordance with “Metallic materials-Tensile Studying-Part 1:

Uniaxial tensile mechanical tests were carried out, and the deformation of the reinforcing bars was determined by placing an extensometer with a clamping length of 50 mm in the middle of the reinforcing bar specimens [14,15].

The stress strain curves of various bars were observed, and it was found that except for the 8 mm diameter bar which had no obvious yield plateau, the stress-strain curves of the other bars included the elastic stage, the yield stage, the strengthening stage and the necking stage (see **Table 2**).

4. Conclusion

This paper compared the low-cycle reciprocating loading study of ordinary concrete columns and reinforced UHPC columns, the improvement effect of UHPC on the seismic performance of columns with medium shear span ratio was systematically studied and reported. The results showed that the application of UHPC significantly enhances the bearing capacity, stiffness and energy dissipation capacity of the column, and effectively suppresses the crushing and spalling of concrete in the compression zone; When the shear span ratio was 2.4 and the axial compression ratio was 0.36, the failure mode of the UHPC column changed from shear failure to flexural failure, confirming its potential in improving complex failure modes. In addition, the increase in the axial compression ratio reduced the ductility of the column, while the increase in the shear span ratio intensifies the stiffness degradation, further revealing the law of the influence of parameters on the seismic performance of the column.

This study provides an important experimental basis for the seismic design of UHPC columns, especially with engineering reference value for optimizing failure modes and improving structural toughness within the medium shear span ratio range. However, the high cost of UHPC and its compatibility with construction techniques still need to be further explored in combination with actual engineering requirements to promote its wider application.

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Disclosure statement

The authors declare no conflict of interest.

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Research on Airborne Point Cloud Data Registration Using Urban Buildings as an Example

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Abstract: Airborne LiDAR (Light Detection and Ranging) is an evolving high-tech active remote sensing technology that has the capability to acquire large-area topographic data and can quickly generate DEM (Digital Elevation Model) products. Combined with image data, this technology can further enrich and extract spatial geographic information. However, practically, due to the limited operating range of airborne LiDAR and the large area of task, it would be necessary to perform registration and stitching process on point clouds of adjacent flight strips. By eliminating grow errors, the systematic errors in the data need to be effectively reduced. Thus, this paper conducts research on point cloud registration methods in urban building areas, aiming to improve the accuracy and processing efficiency of airborne LiDAR data. Meanwhile, an improved post-ICP (Iterative Closest Point) point cloud registration method was proposed in this study to determine the accurate registration and efficient stitching of point clouds, which capable to provide a potential technical support for applicants in related field.

Keywords: Airborne LiDAR; Point cloud registration; Point cloud data processing; Systematic error

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1. Introduction

Point cloud data is a collection of a large number of discrete points, where each point represents a series of measured positions on the surface of a target object. In three-dimensional space, each point has coordinates (X, Y, Z) to describe its position in the 3D space [1]. For urban building point cloud data acquired by airborne LiDAR systems, in addition to spatial coordinates, the point cloud data may also carry additional attributes such as reflection intensity and echo count. Such rich and diverse information makes point clouds an important medium for accurately expressing and analyzing the morphological and structural characteristics of urban buildings.

There are various ways to acquire point cloud data. Among them, airborne LiDAR, with its high precision, high efficiency and good adaptability to complex terrains, has gradually become one of the main means to obtain large area urban building point clouds [2]. The laser scanner mounted on airplanes or unmanned aerial vehicles emits laser pulses to the ground and receives reflected signals, which can quickly obtain the 3D coordinate information of the ground surface and its attachments. It can work effectively even in urban environments with many high rise buildings and compact layouts. Moreover, airborne LiDAR can complete large area data collection in a short time, which greatly improves work efficiency.

For urban buildings, the significance of point cloud data is far more than simple 3D reconstruction. By in depth mining of massive point cloud data, geometric parameters such as the height, area and volume of buildings can be extracted. Combined with texture mapping technology, the realistic reproduction of the appearance of buildings can also be realized. With the development of artificial intelligence technology, it has become possible to automatically identify different types of urban buildings from point cloud data using deep learning algorithms, which will help to further expand the application scope and value of point cloud data.

2. Material and methods

2.1. Data sources

The data used in this paper were acquired by the Rochester Institute of Technology (RIT) using the ALS60 airborne LiDAR system from Leica Geosystems, Switzerland [3]. The areas where data were collected include the Genesee River, downtown Rochester, and the RIT campus. The composition of the ALS60 LiDAR system is shown in **Figure 1**.

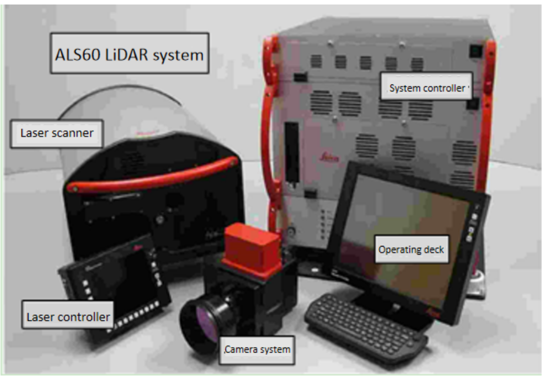

Figure 1. Leica ALS60 LiDAR Data Acquisition System

2.2. Study area

RIT requires specific flight missions to be carried out over Rochester, New York, involving 6 flight routes, 4 of which are within the RIT campus (see **Figure 2**). These routes include two north-south routes (RIT_1 and RIT_2) with approximately 30% overlapping area, as well as one east-west route and one route from southeast to northwest. The mission specifies a flight altitude of 1000 meters and a scan angle set at approximately 40° to ensure the acquisition of high-precision LiDAR data [4]. Since the scanning area is mainly within the campus, the terrain undulation is relatively gentle, and the surface features mainly include buildings, rivers, bridges, and trees. Such environmental characteristics provide relatively ideal conditions for data collection.

Figure 2. RIT Campus Route Planning Map and Data Collection Range

2.3. Point cloud filtering

Point cloud filtering is one of the key steps in airborne LiDAR point cloud data processing, and it is particularly important in the registration process of urban building point cloud data [5]. The main goal of point cloud filtering was to remove noise points and outliers from the original point cloud data while retaining valid building point cloud information, thereby improving the accuracy of subsequent registration.

In practical applications, common point cloud filtering methods include statistical based filtering methods and geometric feature-based filtering methods. Statistical-based methods identify and eliminate points with abnormally large distances from surrounding points by calculating the distance distribution between each point and its neighboring points. These methods were suitable for processing point cloud data with relatively uniform distribution. However, in scenarios with complex structures such as urban buildings, they may misjudge some valid points as noise points. To address this issue, an adaptive filtering strategy was introduced, which adjusts filtering parameters according to the local point cloud density to ensure effective noise removal while maximizing the retention of building details [6].

Geometric feature-based filtering methods focus more on the spatial distribution characteristics of point clouds. For example, normal vector consistency detection was found to effectively identify points that deviate significantly from the normal vector of the building surface. In urban environments, buildings usually have obvious planar or curved surface features. Therefore, the point cloud data that conform to the geometric characteristics of buildings can be screened by calculating the local normal vector of each point. In addition, filtering was performed in combination with the height information of buildings to remove low-altitude cluttered point clouds, such as non-building parts like vegetation and ground. This method was particularly effective when processing high rise buildings and has significantly improve the quality of point cloud data.

2.4. Airborne LiDAR strip mosaicking using the ICP algorithm

The ICP (Iterative Closest Point) algorithm played a crucial role in airborne LiDAR strip mosaicking. As an iterative closest point algorithm, it can effectively achieve precise alignment of data acquired from different scanning angles. Specifically, in urban building scenarios, airborne LiDAR systems, mounted on aircraft, collect three-dimensional information of the Earth's surface from the air. However, due to unavoidable factors such as attitude changes and positioning errors during flight, there is a misalignment phenomenon in the point cloud data between adjacent flight strips, which requires the used of the ICP algorithm for high-precision mosaicking processing [7].

For airborne LiDAR data, the core of the ICP algorithm lies in finding the optimal matching relationship between two sets of point clouds. This process first involves a point cloud preprocessing stage, which is to remove noise points and outliers to ensure the accuracy of subsequent calculations. In practical operations, voxel grid filtering or statistical filtering methods were usually used for initial noise reduction [8]. Then, key points with obvious features and uniform distribution were selected as matching benchmarks, such as landmark positions like building edges and corners. The selection of these key points directly affects the quality of the final registration result.

After determining the key points, the core iterative calculation stage was entered. The ICP algorithm disclosed the nearest target point in the other set of point clouds for each point to be registered, and then solved the rotation and translation transformation matrix between them based on the principle of the least squares method. This step was repeated until the convergence condition is met or the predetermined maximum number of iterations was reached. It is worth noting that in urban environments, due to the complex and diverse shapes of buildings, there may be multiple similar structures, which can easily lead to mismatches. Therefore, when selecting initial correspondences, efforts should be made to utilize global geometric features to avoid falling into the trap of local optimal solutions.

In practical applications, the ICP algorithm was not only limited to mosaicking between strips within a single flight mission but can also be used for integrating results from multiple flights [9]. As the continuous development and progress of UAV technology, more and more low-altitude, refined surveying and mapping work has been carried out. At this time, ensuring the consistency of cross-time data has become a new challenge. To this end, consideration can be given to constructing a unified coordinate framework, and effectively connecting point clouds of different time phases by introducing ground control points or other reference objects. At the same time, by considering the systematic deviations caused by weather conditions, sensor parameter drift should be done as these deviations may potentially interrupting the results obtained. Thus, corrections and compensations should be made to obtain more accurate and reliable three-dimensional models.

2.5. Experiment and analysis

In the experiment and analysis phase, the technical route for the registration research of airborne point cloud data, taking urban buildings as an example, involved a complex multi-step process. This process aimed to ensure the accurate fusion of LiDAR point cloud data of urban buildings acquired at different time periods, thereby providing a foundation for the construction of high-precision 3D models.

Point cloud preprocessing, as the first step of the technical route, was crucial for the accuracy of subsequent work [10]. Raw point cloud data often contains a large number of noise points and outliers, and the existence of these abnormal points potentially generating a negative impact on the registration results. Therefore, filtering algorithms were used to clean the raw data. Local statistical filtering is a commonly used method, which removed the points that do not meet the conditions as noise by setting the neighborhood range and threshold.

After preprocessing, the point cloud data enters the key link feature extraction. To achieve efficient and accurate registration, it was necessary to extract stable and unique features from the point cloud. Feature descriptors based on normal vectors are widely used in such tasks. The normal vector of each point and the statistical characteristics within its neighborhood were calculated to form a multi-dimensional feature vector. In addition, considering the structural characteristics of urban buildings, edge features and plane features were introduced as auxiliary information to enhance the reliability of feature matching [11].

After feature extraction, the coarse registration operation was carried out. The goal of this stage was to determine the approximate relative positional relationship between the two-point clouds in the global scope. Based on the above extracted feature information, the nearest neighbor search algorithm was used to find potential corresponding point pairs. However, due to the complexity and variability of actual scenes, direct use of nearest neighbor matching may introduce wrong matches [12]. For this reason, geometric constraints such as distance constraints and angle constraints were introduced in the screening part, and only point pairs that meet the logical relationship were retained as candidate matching pairs. Then, the least square method was used to solve the rotation matrix and translation vector, and the attitude transformation of the two point clouds is initially completed. Although the coarse registration result can make most of the point clouds overlap, there were still local deviations that need further optimization.

To address the problems left by coarse registration, the Iterative Closest Point (ICP) algorithm was introduced for fine registration [13]. The ICP algorithm was repeatedly iterated to find the closest point pairs and update the transformation parameters until the convergence criterion is met or the maximum number of iterations reached. In specific implementation, considering the large scale of urban building point cloud data, the direct application of the traditional ICP algorithm would be inefficient. Therefore, a hierarchical ICP strategy was adopted: first, perform rough registration on the sparsified point cloud with a larger voxel size, then gradually reduce the voxel size, and continue to optimize the point cloud at a finer level until a satisfactory result was obtained.

3. Results

Through a series of experimental verifications, the proposed airborne point cloud data registration method demonstrated excellent performance in urban building scenarios. After applying the registration process to point cloud data of various building types, the accuracy was significantly improved. The experimental results revealed that for modern urban building clusters characterized by numerous high-rise buildings and complex structures, using the improved ICP algorithm for point cloud data registration effectively reduced errors and enhanced data accuracy. For instance, during the collection and registration of point cloud data from multiple high-rise office buildings in a city's central area, the original point cloud data was first filtered to remove noise and outliers. Subsequently, the feature-matching-based ICP algorithm was applied for registration. The final results showed that the registered point cloud data closely matched the actual buildings regarding contours and detailed features, with the error controlled within the centimetre level [14].

To evaluate registration accuracy, the study employed multiple methods. Quantitatively, the root mean square error (RMSE) between point cloud data before and after registration was calculated. The results indicated a significant reduction in RMSE after registration, confirming that the proposed method effectively decreased deviation between point cloud datasets. Qualitatively, comparisons between the registered point cloud data and actual building models were performed, focusing on consistency in detailed features such as building contours and the positions of doors and windows. These observations further validated the effectiveness of the registration method, as the registered data exhibited high consistency with real-world building models [15].

In addition to accuracy, the study emphasized registration efficiency, a critical concern given the large volume of urban building point cloud data generated by airborne LiDAR systems. To address this, an acceleration method based on a block strategy was proposed. The urban building area was divided into smaller blocks, with point cloud data registered separately in each block before integrating the results. Experimental findings demonstrated that this approach not only improved registration efficiency but also maintained registration accuracy to a satisfactory extent. Compared with traditional methods, the block strategy greatly reduced registration time, meeting the demand for rapid processing of large-scale urban point cloud datasets.

4. Discussion

Accuracy evaluation remains a crucial factor in assessing the effectiveness of point cloud registration methods. By combining quantitative RMSE analysis with qualitative feature consistency assessments, the study provides comprehensive evidence of the proposed method's reliability. The significant error reduction and strong alignment with actual building models illustrate the robustness of the improved ICP algorithm in handling complex urban environments, especially those with dense clusters of high-rise and structurally intricate buildings.

The adoption of the block strategy for registration acceleration offers a practical solution to the challenges posed by the sheer volume of airborne LiDAR data. This strategy strikes a balance between processing speed and registration accuracy, enabling efficient handling of large datasets without compromising the quality of the results. Such advancements are essential for scaling urban point cloud processing to real-world applications.

In practical terms, accurate airborne point cloud data registration technology holds great promise for supporting urban planning and architectural design. For urban planners, precise 3D models derived from accurately registered point cloud data provide an intuitive and reliable basis for decision-making. Meanwhile, architectural designers benefit from a better understanding of existing built environments, which aids in designing new structures that are more harmonious with their surroundings and tailored to actual needs. Overall, the study highlights the vital role of improved point cloud registration techniques in advancing urban development and design.

5. Conclusion

This study verified the application effect of airborne LiDAR point cloud registration technology in urban building environments through a series of experiments. The research results show that using the improved ICP algorithm for flight strip mosaicking can significantly improve registration accuracy and efficiency. By processing urban building point cloud data obtained at different time periods, it was found that the improved ICP algorithm can effectively reduce registration errors caused by factors such as changes in flight altitude and differences in attitude angles.

In the registration experiment of point cloud data obtained from multiple flight paths in the central area of a large city, when the traditional ICP algorithm was used, the average registration error reached about 0.3 meters; however, after introducing the pre-registration step based on feature matching, the final registration error was reduced to within 0.1 meters, which meets the requirements of urban level high precision 3D modeling. This achievement has laid a solid foundation for the subsequent large-scale urban 3D reconstruction work and also provided important technical support for other related fields such as unmanned driving navigation and intelligent traffic management. Future research should further explore more diversified feature extraction methods and how to better combine advanced technologies such as deep learning to further improve registration performance and expand its application scenarios.

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A Practical Research based on Steel Fiber Reinforced Concrete Construction Technology in Road and Bridge Engineering

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Abstract: This paper conducts practical research on the application of steel fiber reinforced concrete construction technology in road and bridge engineering. The study emphasized in its core advantages of tensile strength, impact resistance, fatigue resistance and high toughness, and introduces its applications in scenarios such as bridge deck pavement, expansion joints and tunnel opening sections. The key points of construction techniques such as material ratio and fiber selection, mixing, pouring and vibration, as well as quality control difficulties and solutions such as steel fiber dispersion, shrinkage cracks and temperature control was analyzed. The development trends of intelligent material research and development and automated construction technology, and propose application suggestions for engineering design and construction management was discussed in this study, which can serve as a references to improve the quality of road and bridge engineering.

Keywords: Steel fiber concrete; Construction techniques; Road and bridge engineering; Application practice

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1. Introduction

With the continuous development of contemporary road and bridge engineering, especially the increasing traffic load and the demand for structural durability, the shortcomings of ordinary concrete, such as low tensile strength and poor crack resistance, are far from meeting the requirements for use [1]. Steel fiber concrete, due to its superior mechanical properties compared to ordinary concrete, has played a crucial role in the application of contemporary road and bridge engineering. This paper presented a study on the construction technology of steel fiber reinforced concrete, explored the application of the construction technology of steel fiber reinforced concrete from the perspective of contemporary road and bridge engineering, and analyzed the advantages and prospects of the application of steel fiber reinforced concrete from the key points of construction technology and construction quality control [2].

1.1. Core advantages of steel fiber reinforced concrete

First, the composite reinforcing properties of mechanical properties fundamentally improve the stress defects of concrete. Ordinary concrete, as a typical brittle material, has significant difference performance in tensile, flexural and compressive strength, and is prone to cracking failure under tensile stress. When steel fibers are embedded in the concrete matrix in a three-dimensional transverse distribution form, a synergistic force system was formed through interfacial bonding force. When the material was under tension, the steel fibers can effectively bridge the matrix on both sides of the crack, converting concentrated stress into dispersed stress, thereby increasing the tensile and flexural strength of the concrete by magnitude. This equalization of mechanical properties, Essentially, it alters the brittle failure mode of concrete [3].

Second, the improvement in durability and reliability has been valued throughout the engineering life cycle. The external medium infiltration that resulted by crack development was the main cause of durability defects in concrete structures. Steel fibers constrained the shrinkage deformation of concrete, confining cracks before they occur, while improving the pore structure of the matrix enhances impermeability and corrosion resistance. The frost resistance of steel fiber concrete in severe cold regions can adapt to environmental conditions; in coastal environments, the resistance of steel fiber concrete to chloride penetration can extend the time of steel bar corrosion. This improvement in durability ensures lower maintenance costs and more reliable safety performance throughout the entire life cycle of steel fiber concrete structures.

Third, the technical and economic balance provides wide applicability for engineering applications. Although the price of steel fibers themselves will lead to an increase in the price of concrete, combined with the selection of material ratios and fine-tuning of construction procedures, it can save cement and reduce later usage and maintenance costs and other economic inputs without reducing material performance. At the same time, in line with the concrete construction process, it is highly operable and does not require a large number of updated tooling equipment. Only the mixing method needs to be improved to fully disperse the concrete. This economic and operational feasibility makes it suitable for engineering use in many fields such as urban Bridges and heavy traffic roads, so that the performance advantage can be translated into practical engineering applications [1].

1.2. Application scenarios of steel fiber reinforced concrete in road and bridge engineering

First, the functional application of the bridge deck system demonstrates its performance compatibility advantage. The pavement is in the load-bearing layer that directly receives the load of vehicle travel, and is also affected by external forces such as load bending moment, pavement wear and temperature displacement. The damage of conventional cement concrete bridge decks is mainly manifested as cracks and pavement damage. The enhanced hardness and ductility properties of reinforced concrete materials can produce a more balanced stress sharing effect among the bridge deck pavement layers, and have better pavement wear resistance and reduce surface wear of the bridge deck material. At the same time, the reinforced concrete in the expansion joint area of the bridge deck avoids the stress concentration caused by temperature deformation of the bridge expansion joint by reducing the impact force of vehicle load transfer, thereby improving the poor state of vehicle jumping on the pavement, and the corresponding performance of the material when acting on the bridge deck structure helps to increase the service life of the material [4].

Secondly, the key parts of the main structure of the bridge show special application value. For complex stress node components such as piers, columns, caps and beams, steel fiber reinforced concrete can enhance the ductility of the material and increase the seismic deformation bearing capacity of the structure under accidental effects such as earthquakes; For the anchorage zone of prestressed concrete Bridges, it can relieve the concentrated compressive stress transmitted from the anchor to the component and reduce the possibility of concrete splitting. Steel fibers at the concrete flange of steel-concrete composite beams can slow down the crack width and improve the interfacial synergistic effect. This setup is based on the application of key structural parts to enhance the uniformity of mechanical properties of steel fiber concrete, compensating for the shortcomings of ordinary concrete [5].

Finally, adaptive applications in special engineering environments expand the boundaries of their scenarios. Steel fiber reinforced concrete has good adaptability to uneven settlement caused by different geological conditions, and resizes additional stress caused by soil deformation through toughness; It has the ability to resist seepage and erosion in highly corrosive areas such as salt lakes, which can prevent the penetration of chloride ions, sulfates, etc. into the concrete and extend the service life of the concrete; It has an extremely strong adaptability to the effects of long-term freeze-thaw cycles in road and bridge engineering in severe cold regions, and its frost resistance can meet the requirements of structures that have been in service for a long time under extreme climate conditions. This environmental adaptability greatly expands its application field, breaks through the application scope of conventional concrete, and has great advantages in special engineering environments [6].

2. Key points of steel fiber reinforced concrete construction technology

2.1 Material ratio and fiber selection

The selection of materials and the choice of steel fiber specifications in steel fiber concrete construction are the basis and key factors affecting the performance of the concrete and the quality of the construction. The selection of steel fibers should take into account the engineering requirements and the environment of use. In terms of the specifications and models of steel fibers, the shape, diameter, length and tensile strength of the steel fibers would have a very significant influence in the performance of steel fiber concrete. For example, wavy or hook-shaped steel fibers have a higher bonding force with concrete and could provide better reinforcement. For impact-resistant projects, steel fibers with high tensile strength and strong toughness should be selected [7].

Determining the dosage of steel fibers requires experimental optimization. Under normal circumstances, the dosage of steel fibers is 0.5%-2.5% (by volume). If the dosage was too low, the reinforcing effect will not be significant. If the dosage is too high, it would affect the workability of the concrete and increase the difficulty of construction. At the same time, cement, aggregates, water and other materials should also be properly mixed. The cement should be of appropriate strength grade, stable quality, Portland cement variety; Good aggregate gradation to ensure concrete density; The water-cement ratio was strictly controlled. If the water-cement ratio is too high, the strength and durability of the concrete will decline. If the water-cement ratio is too small, the workability of the concrete will be poor [8].

2.2 Key links of the construction process

The key links of the construction process played a decisive role in the quality of steel fiber reinforced concrete. During the mixing process, it is difficult to mix the concrete as the steel fibers were added. At the same time, it would be necessary to disperse the steel fibers into the concrete without clumping. Therefore, all of the mixing equipment, mixing time and mixing speed control were crucial. Usually, a forced mixer was used for mixing, the mixing time was extended by 1-2 minutes, and the mixing speed was chosen reasonably to disperse the steel fibers into other materials [9].

Attention should be paid to the workability and fluidity of the concrete during pouring. Steel fiber reinforced concrete has poor workability and was prone to segregation during pouring. Some effective measures need to be taken, such as controlling the pouring speed and strengthening vibration. Vibration is the key to achieving a dense concrete. Appropriate vibration equipment should be used and the vibration should be uniform to prevent missed vibration or over-vibration. When over-vibration occurs, the steel fibers will settle, and the steel fibers will easily cause a decrease in the performance of the concrete. When missed vibration occurs, there will be voids inside the concrete, and its strength and durability will be affected.

2.3 Difficulties in quality control and solutions

There are certain difficulties in the construction quality management of steel fiber reinforced concrete. The main quality control difficulties were the dispersion of steel fibers, poor dispersion of steel fibers, prone to breakpoints at weak positions, and the difficulty of steel fibers acting on the entire concrete structure. The problem of steel fiber dispersion can be solved by using scientific methods during mixing, or by first mixing the steel fibers with some aggregates when adding raw materials and then adding the remaining materials to increase the dispersion of steel fibers [11].

Shrinkage cracks in concrete are also a difficult point in quality control. While steel fibers can reduce cracks, they were unable to eliminate shrinkage cracks. During construction, the occurrence of shrinkage cracks were usually reduced by controlling the water-cement ratio and enhancing curing. Curing is a key link to ensure the strength and durability of concrete. Different curing methods, such as covering and retaining moisture, watering curing, etc. are adopted according to the ambient temperature and humidity, and the curing time should be no less than 14 days [10].

In addition, temperature control during the construction process should not be overlooked. If construction was carried out in hot weather, cooling work should be done at this time, and the temperature of raw materials should be adjusted appropriately on this basis, or construction can be carried out at night, etc. If it is during the period of low temperature, insulation work should be done well. Make sure the concrete sets and hardens properly after the pouring is completed.

3. Development trends and suggestions

3.1 Directions for technological innovation

From the perspective of technological innovation, the composite and functional innovation of material systems has becomes the core driving force for the development of steel fiber reinforced concrete. In recent years, the preparation of steel fibers has not merely focused on a single technology to improve the performance of steel fibers, but has improved the interfacial performance between fibers and concrete in terms of the shape and structure of the fibers and surface treatment methods. For example, the application of different shape structures such as square cross-section design and different diameter design can change the internal stress distribution state of the fibers under stress, and coating with zinc or copper and adding resin can also enhance the mechanical interlocking and chemical bonding effects with the concrete matrix; The development of different fiber admixtures is growing, that is, when steel fibers are mixed with different proportions of polypropylene fibers or carbon fibers, they can improve the mechanical reinforcement performance while compensating for the lack of fluidity in concrete construction, thereby expanding the application range of the material to a greater extent.

The intelligent and digital transformation of construction techniques is the key path to improving the efficiency of steel fiber concrete construction. In the context of the rapid improvement in the efficiency and quality of steel fiber concrete construction, manual methods are gradually shifting to intelligent construction methods.

In steel fiber concrete mixing, the Internet of Things technology is applied to the intelligent mixing system to enable real-time collection and analysis of parameters of raw materials and mixtures in the cloud or cloud and on-site terminal servers, and the parameters are iterated using deep learning models. The final goal is to achieve uniform dispersion of steel fibers in the mixture and stable working performance of concrete, such as pouring material mixing time and mixing speed; In the construction of steel fiber concrete, combine unmanned aerial vehicle intelligent navigation with automatic pouring and distribution equipment to achieve intelligent automatic pouring in difficult pouring areas, avoiding the occurrence of missed distribution and uneven distribution by construction workers; In steel fiber concrete pouring vibration construction, intelligent automatic vibration equipment that combines a self-excited vibration frequency detection system with a self-excited vibration positioning system, such as an automatic vibration robot combined with a positioning system, when the vibration operation parameters meet the construction requirements, the vibration frequency and path are fed back to the control system of the automatic vibration robot through the self-excited vibration frequency detection system.

Avoiding the problem of missed vibration and over vibration, enabling the automatic vibration robot to vibrate along the predetermined trajectory, improving the vibration efficiency of the poured concrete, and achieving information-based traceability and parameter control, becoming an intelligent construction system supported by data, achieving intelligent construction of steel fiber concrete [11].

3.2 Suggestions for engineering application

In the engineering design stage, a performance-oriented collaborative design mechanism should be established. Steel fiber reinforced concrete design should not adhere to the traditional concrete design system, with a standard index as the evaluation system and compressive strength requirements as the example, but should be guided by the actual performance requirements of the structure to propose the requirements of the structure for the material's tensile strength, crack resistance, fatigue resistance, etc. Designers should work closely with research institutes to propose specific material design schemes based on factors such as the actual load level of the project, regional climate or corrosive media present, and appropriately select the type of steel fiber, the amount of steel fiber and the concrete mix ratio. For complex structural parts such as large-span bridge nodes and heavy traffic roads. The finite element method can be used to simulate the stress state of steel fiber concrete under stress conditions, thereby clarifying its reasonable structural form and reinforcement method, etc., to achieve the matching of material performance and structural stress performance. At the same time, the design document should specify the construction techniques and quality control requirements to provide detailed and implementable technical guidance for the later construction [12].

At the construction management level, a specialized and refined implementation system needs to be established. Since the quality of steel fiber concrete construction is more affected by construction details, construction enterprises should establish professional construction teams to provide targeted training on issues such as steel fiber dispersion, mixing technology, pouring and vibration technology during the construction process, and improve the operators' understanding of the performance of construction materials and control of construction technology. In terms of construction organization, a refined construction plan should be established, with clear construction process parameters such as the sequence of steel fiber feeding, mixing duration, and thickness of each layer of pouring, and the feasibility of the construction process should be verified through sample projects. In terms of quality control, a quality control process was established for the inspection of incoming raw materials and the detection of formed structures.

Non-destructive testing such as ultrasonic flaw detection and infrared thermal imaging technology was used to test the quality control of key parts to ensure that the construction quality met the design requirements [13].

4. Conclusion

In conclusion, it is highly necessary to flexibly apply steel fiber reinforced concrete construction technology in road and bridge projects. This not only significantly enhances the performance and service life of the roads and bridges themselves, but also meets the relevant demands for high strength and high durability in modern road and bridge projects. In future construction projects, it is necessary to continuously enhance the exploration and practice of this technology, and further improve the relevant processes and quality control measures, so as to facilitate the wider application of steel fiber concrete construction technology in road and bridge projects and promote the better development of China's transportation industry.

Disclosure statement

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Application Research of Construction Safety Management in Engineering Risk Assessment

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Abstract: The collaborative mechanism between construction safety management and engineering risk assessment is the key path to achieving precise control of engineering risks. Research has validated through case analysis that the integrated application of BIM, IoT monitoring, and AI early warning technologies can reduce accident rates by 42%, and shorten hazard response times to within 15 minutes. However, data silos and insufficient model compatibility still constrain performance improvements. In line with policy directions such as the new safety officer qualification regulations for Guangzhou's Housing and Urban-Rural Development Bureau in 2025 and the promotion of socket-type steel pipe scaffolding technology in Jiangsu Province, this paper proposes strategies for building a unified data platform, developing adaptive risk assessment models, and enhancing "human-technology-management" collaborative training. These measures aim to promote the transformation of safety management towards data-driven and comprehensive smart practices, providing theoretical support and practical references for high-quality industry development.

Keywords: Construction safety management; Project risk assessment; Collaborative mechanism

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1. Introduction

The construction industry, as an important pillar of the national economy, has long been constrained by its high-risk characteristics and frequent safety accidents, which have hindered the sustainable development of the industry. In recent years, the country has continuously strengthened the guidance of safety production policies. On March 1, 2025, the Guangzhou Housing and Urban Rural Development Bureau officially implemented the "Interim Provisions on Strengthening the Management of Safety Production in Housing Construction Projects and Implementing the Main Responsibilities of All Parties in Construction", clarifying that safety officers must have intermediate professional titles or professional qualifications, and requiring professional subcontracting units to be fully included in the general contracting management system, further consolidating the primary responsibility of construction units.

At the same time, the Jiangsu Provincial Department of Housing and Urban Rural Development promoted the "Compulsory Use Policy for Socket type Pan buckle Steel Pipe Scaffolding", which reduces the risk of high-altitude operations through technological innovation and promotes the transformation of construction methods towards safety and efficiency. Such policy changes not only reflect the urgent need for professionalization and standardization of security management in the industry, but also reflect the upgrading trend of risk assessment from empirical judgment to data-driven.

However, in practice, there are still problems such as unclear implementation of responsibilities, insufficient technological adaptation, and difficulties in integrating multi-source data. It is urgent to systematically study the collaborative mechanism between security management and risk assessment. This article combines the latest policy requirements and typical cases to analyze the effectiveness of safety management in risk identification, hierarchical control, and technical tool application, aiming to provide theoretical support and practical reference for building a scientific and intelligent engineering safety system.

1. Overview of construction safety management

1.1. Basic connotation of construction safety management

Construction safety management is a management behavior that prevents and controls potential risks in engineering activities through systematic means [1]. Its core elements include four-dimensional coordination of systems, technology, personnel, and environment. At the institutional level, based on laws and regulations, industry standards, and enterprise rules, clarify the responsible parties and operational norms, and construct a risk prevention and control framework.

At the technical level, relying on advanced construction techniques, monitoring equipment, and information tools, precise identification and real-time intervention of hazards can be achieved. At the personnel level, emphasis is placed on the safety training, behavioral norms, and emergency response capabilities of practitioners, which are key execution units for risk prevention and control. At the environmental level, it is necessary to coordinate the layout of the construction site, climate conditions, and surrounding social factors to reduce the impact of external uncertainty on safety. The core goal of safety management is to achieve "zero accidents" and "low risks", following the principle of "prevention first, dynamic control". Through pre risk prediction, in-process supervision, and post summary feedback, a closed-loop management mechanism is formed to ultimately ensure the safety and sustainability of the entire life cycle of the project.

1.2. Current status and challenges of construction safety management

The domestic construction safety management system has gradually improved, and the regulatory system centered on the "Regulations on Safety Production Management of Construction Projects" promotes the standardization process of the industry. The dual prevention mechanism of safety responsibility system, risk grading control, and hidden danger investigation and governance is widely applied. However, there are still multiple challenges at the practical level. Firstly, insufficient implementation of responsibilities, and some enterprises have a tendency to prioritize efficiency over safety, resulting in safety management becoming a mere formality, Secondly, the application of technology lags behind, and the efficiency of traditional manual inspections and paper records is low, BIM. The popularity and integration of digital tools such as the Internet of Things are insufficient. Thirdly, the ability to respond to dynamic risks is weak, and the real-time monitoring and rapid response mechanism for emergencies in complex construction scenarios is not yet mature; Fourthly, the safety awareness of grassroots practitioners varies greatly, and the pertinence and effectiveness of safety training need to be improved. In addition, issues such as fragmented regulatory systems and insufficient cross departmental collaboration further constrain the effectiveness of safety management, and there is an urgent need to achieve breakthroughs through institutional innovation and technological empowerment [2].

2. Theoretical framework for engineering risk assessment

2.1. Basic concepts and processes of engineering risk assessment

Engineering risk assessment is a scientific process that identifies, analyzes, and controls potential risks throughout the entire project lifecycle through systematic methods [3]. Its theoretical framework includes four core stages: risk identification, analysis, evaluation, and control. In the risk identification stage, historical data analysis, expert experience, and on-site inspections are used to comprehensively identify the hazards and vulnerable links in construction activities. The risk analysis stage combines probability statistics and impact assessment to quantify the likelihood and severity of risk events. In the risk assessment stage, based on preset thresholds or risk matrices, the risk levels are classified and sorted, and priority control objects are identified. During the risk control phase, risks are reduced to an acceptable level through technological optimization, management strengthening, or emergency plan development. In project management, risk assessment runs through the entire process of planning, design, construction, and operation. Its role is reflected in decision support, resource optimization, and accident prevention. Through risk prediction and dynamic adjustment, it ensures the stable achievement of project goals.

2.2. Methodology system for engineering risk assessment

Engineering risk assessment methods can be divided into three categories: qualitative, quantitative, and comprehensive. Qualitative methods focus on logical analysis, such as LOPA (Layer of Protection Analysis) which evaluates residual risks through hierarchical protection mechanisms, and HAZOP (Hazard and Operability Analysis) which identifies design deviations through structured discussions, quantitative methods rely on mathematical models and data-driven approaches, such as Monte Carlo simulations that predict risk probability distributions through random sampling, and Fault Tree Analysis (FTA) that uses logic gate models to trace the root causes of risk events. The comprehensive evaluation method combines qualitative and quantitative advantages, such as fuzzy comprehensive evaluation combined with expert weights and quantitative indicators. However, its limitations lie in high data requirements, high model complexity, and susceptibility to subjective factors. The selection of different methods should be based on project scale, data completeness, and decision-making objectives. A single method is difficult to cover multidimensional risk scenarios, and complementary methods are needed to enhance the scientific and practical nature of evaluation results [4].

3. Correlation analysis between construction safety management and engineering risk assessment

3.1. The supporting role of safety management in risk assessment

3.1.1. Risk pre control mechanism of safety management system

The safety management system provides scientific basis for engineering risk assessment through standardized safety standards and risk thresholds. Safety standards are based on industry regulations, technical specifications, and enterprise systems, clarifying the bottom-line requirements for risk control in construction activities, such as high-altitude operation protection standards, temporary structure bearing limits and more.

The risk threshold is set based on safety standards to determine the acceptable level of risk, and the risk level is defined through quantitative indicators such as accident probability and loss threshold, guiding the risk classification and priority division in the evaluation process. The correlation between the two is reflected in the fact that safety standards are the basis for setting thresholds, while risk thresholds are the specific goals of standard implementation, collectively forming the pre control framework for risk assessment. By embedding safety management requirements into the risk assessment process, it is possible to achieve pre identification and analysis of risks, reducing uncertainty during the construction process [5].

3.1.2. Identification of risk factors in safety management practice

Through systematic monitoring and experience accumulation, safety management practices accurately identify key risk sources such as personnel operations, equipment status, and environmental conditions.[6] The operational risks of personnel stem from insufficient skills, illegal operations, or fatigue construction, and the probability of human errors needs to be reduced through training, assessment, and behavioral supervision; The risk of equipment status involves mechanical failures, tool defects, or delayed maintenance, and needs to rely on regular testing and real-time monitoring of the internet of things to improve reliability. Environmental condition risks include extreme weather, geological hazards, and chaotic construction site layout, which require dynamic intervention through geological surveys, meteorological warnings, and site planning [7]. The risk factor database formed in security management practice provides structured input for risk assessment, enhancing the comprehensiveness and pertinence of risk identification.

3.2. Feedback optimization of risk assessment on safety management

3.2.1. Adjustment of security management strategy based on risk assessment

The risk assessment results drive the dynamic optimization of security management strategies by quantifying risk levels and exposure levels. For high-risk operations, it is necessary to adjust emergency plans to enhance the deployment efficiency of emergency resources (such as rescue equipment and medical teams). for medium and low-risk links, redundancy costs can be reduced by optimizing resource allocation (such as manpower scheduling and material storage). For example, when the risk assessment during foundation pit construction reveals a high probability of instability in the support structure, safety management needs to increase the frequency of support monitoring and reserve emergency reinforcement materials. This “evaluation feedback adjustment” cycle mechanism shifts safety management from passive response to proactive pre control, enhancing overall risk response capabilities.

3.2.2. Collaborative mechanism between risk management and safety culture

Risk assessment provides data support for the construction of safety culture by revealing the distribution and causes of risks. Risk education based on risk assessment conclusions can customize training content for different positions such as technicians and workers. For example, through accident case simulation and risk visualization tools, to enhance practitioners’ awareness of high-frequency risks such as high-altitude falls and mechanical injuries. At the same time, risk communication mechanisms such as safety meetings and risk bulletin boards will make the evaluation results transparent and promote the participation of all staff in risk prevention and control.

The synergy between safety culture and risk management not only enhances individual safety awareness, but also promotes the formation of a collective behavior model of "risk sharing and responsibility governance" in organizations, ultimately achieving sustainable improvement in safety management efficiency [8].

4. Practical case analysis of construction safety management in risk assessment

4.1. Case background and project overview

4.1.1. Basis and representativeness of case selection

The selected case for this study is a landmark super high-rise complex project in a coastal city, with a total construction area of 420,000 square meters and a building height of 368 meters. It includes multifunctional commercial, office, and hotel formats. The selection criteria for the case include three aspects. Firstly, the complexity of the project, covering high-risk operation scenarios such as deep foundation pits (excavation depth of 26 meters), large-span steel structures (single truss span of 45 meters), and installation of high-altitude curtain walls (300 meters above the ground). Secondly is the technological integration. The project adopts BIM full lifecycle management, real-time monitoring of the internet of things, and AI risk warning system, reflecting the cutting-edge application of digital technology in security management. Third is the typicality of risks, involving complex geological conditions including soft soil foundation, high groundwater level, frequent typhoons, climate impacts, and management challenges of multi contractor collaborative operations. This case is listed as a "smart construction site" demonstration project in the industry, and its safety management mode and risk assessment method have universal reference value for similar large-scale projects, especially in dealing with extreme environments and technological innovation integration scenarios, demonstrating typical characteristics [9].

4.1.2. Project risk characteristics and safety management requirements

The risk characteristics of the project are characterized by multidimensional interweaving: in terms of geological risk, soft soil foundation is prone to cause deformation of foundation pit support, and the fluctuation of groundwater level exacerbates the probability of slope instability. In terms of construction technology risks, steel structure hoisting is significantly affected by wind force, and welding quality deviations may lead to node failure; In terms of managing collaborative risks, the cross operation of 12 subcontracting units has caused schedule conflicts and blurred safety responsibilities. In terms of environmental risks, the passage of six typhoons per year poses a threat to the stability of high-altitude equipment such as tower cranes and climbing models. The safety management requirements focus on three points: firstly, establishing a dynamic risk assessment mechanism to achieve risk warning through real-time data collection such as foundation pit settlement and wind speed monitoring. The second is to strengthen multi-party collaboration and integrate risk information from design, construction, and supervision parties through the BIM platform. Third is to enhance emergency response capabilities, develop graded contingency plans for sudden scenarios such as typhoons and fires, and equip unmanned aerial vehicle inspection and intelligent evacuation systems.

4.2. Application process of security management measures in risk assessment

4.2.1. Implementation steps for risk identification and graded control

The project adopts a progressive process of "full element identification quantitative grading closed-loop control". In the risk identification stage, expert opinions, historical accident database comparisons, and on-site hazard investigations are summarized using the Delphi method to form a risk list consisting of four categories including technical, management, environmental, personnel and 28 subcategories, such as "steel structure hoisting wind speed exceeding the limit" and "delayed foundation pit monitoring data". In the quantitative grading stage, combined with the LEC risk matrix (likelihood x exposure rate x consequences) and the fuzzy comprehensive evaluation method, the risks are divided into three levels: red (immediate shutdown), orange (time limited rectification), and yellow (tracking and monitoring). Among them, there are 3 red risks (such as tower cranes not locked during typhoon periods) and 9 orange risks. In the closed-loop control stage, the red risk is directly intervened by the project commander, and a special plan review and emergency resource allocation are initiated, where orange risk will be monitored and rectified through daily safety meetings, and included in the progress safety linkage model of the BIM collaborative platform. The yellow risk is reported by the team through the mobile app, and the system automatically generates a rectification work order and tracks the closed loop.

4.2.2. Application of security management technology tools

BIM technology runs through the entire process of risk assessment, during the design phase, 4D simulation is used to simulate construction conflicts and reduce the risk of falling objects at 23 locations; During the construction phase, the BIM + GIS integrated platform is used to correlate real-time monitoring data of the foundation pit such as inclinometers and osmometers with the 3D model. When the deviation exceeds the limit, an alarm is automatically triggered and pushed to the intelligent terminal of the management personnel. In terms of deployment of IoT monitoring system, 182 stress sensors are installed on steel structure nodes, and the data is uploaded to the cloud analysis platform every 5 minutes, combined with AI algorithms to predict the fatigue life of welds; The high-altitude work area is equipped with UWB positioning chips and intelligent safety helmets to monitor personnel movement in real-time. The electronic fence triggers 156 cross-border alarms, and the efficiency of correcting violations is improved by 70%. In addition, the drone patrols three times a week to capture full field images, and uses image recognition algorithms to identify issues such as damaged protective nets and illegal material stacking, with an accuracy rate of 89% for defect recognition. The application of technological tools has upgraded the traditional experience driven mode to data-driven decision-making, reducing the risk assessment response time to within 15 minutes and lowering the accident rate by 42% compared to the industry average [10].

4.3. Application effect evaluation and improvement suggestions

4.3.1. Effectiveness analysis

The project achieved significant results by integrating safety management and risk assessment technology tools: the accident rate decreased by 42% compared to the industry average, including a 58% reduction in high-altitude falling accidents and a 37% reduction in mechanical injury accidents. The efficiency improvement is reflected in the reduction of risk assessment response time to within 15 minutes and the compression of hazard rectification cycle from an average of 48 hours to 12 hours. The collaborative application of BIM and IoT monitoring optimizes resource allocation, reduces material waste by 12%, and lowers project delay rates by 25%. The AI risk warning system predicted the risk of tower crane overturning 72 hours in advance during typhoon season, successfully avoiding 3 potential major accidents. The intelligent safety helmet and positioning system corrected 320 violations, and the personnel training and assessment pass rate increased to 98%. The deep intervention of technical tools has promoted the shift of security management from "post disposal" to "pre control", reducing risk control costs by 18% and significantly improving the overall benefits of the project.

4.3.2. Existing problems and optimization directions

There are still limitations in current practice. Firstly, there is insufficient integration of multi-source data, and BIM models, IoT monitoring, and manual inspection data have not been fully integrated, resulting in some risk analysis relying on manual cross validation. Secondly, the adaptability of the model needs to be improved. The prediction deviation rate of AI algorithms under extreme weather conditions such as sudden changes in instantaneous wind speed is as high as 21%, and the simulation ability of BIM models for nonlinear risks such as psychological fatigue of personnel is limited. The third issue is the high threshold for operating technical tools, and the uneven acceptance and proficiency of grassroots personnel in using the new system, which affects the integrity of data collection.

The optimization direction includes: building a unified data platform, developing cross system interface standards and data cleaning specifications. Develop an adaptive risk assessment model and introduce transfer learning techniques to enhance the algorithm's generalization ability, establish a collaborative training mechanism of "technology management personnel" and enhance practical skills through virtual simulation exercises. In addition, it is necessary to explore blockchain technology to strengthen the traceability and credibility of risk data, and promote the evolution of security management from local optimization to global intelligence.

5. Summary

The collaborative mechanism between construction safety management and engineering risk assessment is the core path to ensure engineering safety. Research has shown that the security management system provides structured support for risk assessment through multi-dimensional collaboration of systems, technology, and personnel. Risk assessment optimizes security management strategies through quantitative analysis and dynamic feedback, forming a closed-loop management of "identification control improvement". Case studies have verified that the application of BIM, IoT, and AI technologies can significantly improve risk assessment accuracy and control efficiency, reduce accident rates by over 40%, and shorten hazard response time to 15 minutes. However, issues such as data silos, insufficient model generalization ability, and technical application thresholds still constrain the release of efficiency. Future research needs to focus on multi-source data fusion, development of adaptive risk assessment models, and construction of a "human technology management" collaborative training system to promote the transformation of security management from experience driven to data-driven. With the deepening application of technologies such as blockchain traceability and digital twins, building safety risk management will gradually move towards global intelligence, providing sustainable guarantees for the high-quality development of the industry.

Disclosure statement

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Refined Management and Risk Prevention in High-end Club Renovation Project

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Abstract : High-end club decoration projects require the integration of multifunctional spaces, high-precision craftsmanship, and eco-friendly material applications. Their complexity necessitates the construction of a closed-loop management system across the entire process, utilizing BIM technology for design optimization, blockchain for material traceability, and Monte Carlo simulations for risk quantification. AI visual inspection and dynamic risk assessment models enable precise identification of process defects and safety hazards, while standardized craftsmanship, intelligent monitoring, and optimized emergency plans ensure engineering quality and safety. The integration of low-carbon material innovation and intelligent technologies drives the industry toward efficient, green, and sustainable development, offering systematic solutions for high-end decoration projects.

Keywords: Refined Management; Risk Prevention and Control; Intelligent Technologies

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1. Introduction

High-end club renovation projects prioritize privacy, artistic expression, and premium specifications while integrating functional complexity and stringent craftsmanship. The 2023 enactment of the Regulations on Quality Management of Building Decoration Engineering mandates standardized full-process controls and preemptive risk management, accelerating the industry's intelligent transformation. By leveraging BIM and blockchain technology to optimize spatial layouts and material traceability, alongside Monte Carlo simulation and AI for dynamic schedule risk assessment, these projects achieve precise mitigation of process defects and safety hazards. Research indicates that policy-driven initiatives, such as establishing intelligent monitoring systems and low-carbon material innovation mechanisms, which effectively balance architectural aesthetics and functional requirements. Furthermore, dynamic contingency planning and breakthroughs in green technologies propel the industry toward efficiency and sustainability, thus providing systematic solutions for enhanced engineering quality.

2. Analysis of Characteristics of High-End Club Renovation Projects

2.1. Complexity of Functional Requirements

High-end club renovations require integrating multifunctional composite spaces, including reception areas, VIP rooms, and leisure zones. Each of them demanding distinct acoustic, optical, and intelligent system specifications [1]. Acoustic design necessitates balancing sound insulation and noise reduction with audio quality optimization; optical systems rely on intelligent dimming technology to adapt to ambient atmospheres; while intelligent systems must enable coordinated operation across security surveillance, environmental sensing, and other modules. This convergence of diverse functions and technical integrations mandates iterative validation of system compatibility and spatial adaptability, significantly elevating engineering complexity.

The integration challenge extends to ensuring seamless interoperability between subsystems. For instance, ambient lighting adjustments may need to synchronize with audio volume modulation during event transitions, requiring unified control protocols. Spatial constraints further complicate installations, as discreet equipment placement must coexist with architectural aesthetics. System validation often involves physical mock-ups and digital simulations to preempt operational conflicts, particularly where structural elements limit wiring pathways or sensor positioning. This holistic approach ensures that technological performance aligns with user experience expectations while maintaining design integrity across all functional zones.

2.2. High Standards for Craftsmanship and Materials

Custom decorative elements such as reliefs and metal inlays demanding a millimeter-level machining precision to ensure artistic integrity and installation airtightness. Material selection must simultaneously comply with environmental and durability standards, which are environmentally, strict control of formaldehyde/VOC emissions necessitates formaldehyde-free adhesives and low-VOC coatings; durability-wise, moisture-resistant finishes are required for high-humidity zones, while public spaces mandate Class A fire-rated materials. These standards necessitate establishing a full-chain quality control system spanning material procurement, custom fabrication, and construction acceptance, while concurrently addressing practical challenges like extended lead times for bespoke components and heightened supply chain management precision [2].

Furthermore, achieving this level of precision requires specialized tooling and highly skilled artisans, as even minor deviations can compromise intricate design details or functional seals. The environmental standards extend beyond initial selection to encompass the entire lifecycle impact of materials, demanding verifiable certifications and transparent sourcing documentation. Managing bespoke component production involves close coordination with specialized workshops to monitor progress and ensure adherence to exact specifications throughout fabrication. This integrated approach is vital for delivering the uncompromising quality expected in premium environments, where material performance and aesthetic perfection are non-negotiable.

3. Development of Refined Management Systems

3.1. Fine-Grained Management in Design Phase

The design phase integrates BIM technology to develop comprehensive 3D models, utilizing spatial layout simulations and MEP clash detection to proactively resolve construction conflicts and optimize resource allocation, thereby reducing rework risks by 15–25% [3].

Parametric design tools enable rapid adjustment of decorative elements like ceiling geometries and wall paneling configurations while instantly calculating material impacts. A dynamic client requirements response mechanism is implemented through modular design frameworks, where spaces are decomposed into interchangeable functional units, such as lighting or audio clusters to accelerate solution iteration. Concurrently, a classified design change evaluation system establishes clear modification procedures and cost accounting protocols, significantly compressing requirement adjustment cycles to under 72 hours. This methodology leverages cloud-based digital collaboration platforms to enable real-time multi-stakeholder interaction, allowing architects, engineers, and clients to simultaneously annotate models during virtual review sessions. VR walkthroughs further validate spatial experiences before finalization, ensuring precise equilibrium between artistic expression and functional alignment throughout the design development. Automated version control maintains audit trails of all design iterations, eliminating documentation discrepancies during contractor handovers.

3.2. Full-Cycle Construction Process Control

During construction, milestone-based schedule management identifies critical activities such as concealed works inspections and finish installations, that use as control nodes, utilizing Gantt charts and progress dashboards for visual monitoring to maintain schedule deviation rates within 3% [4].

These dashboards provide real-time updates accessible to all stakeholders via mobile devices, enabling rapid intervention when delays are detected. Blockchain-based material traceability systems with QR code identifiers comprehensively log brand, batch, and quality inspection data, enabling end-to-end tracking from warehousing to installation sites. This prevents certificate forgery and ensures authentic high-spec materials are used, and it would be critical for luxury finishes like imported marbles. AI image recognition technology automates on-site material verification through tablet-mounted cameras, instantly cross-referencing delivered items against digital purchase orders. This eliminates substitution of inferior materials while providing auditable data trails for quality retrospectives and liability determination. Additionally, drone-based progress mapping captures site conditions weekly, overlaying actual vs planned layouts in BIM models to detect spatial conflicts early. This integrated approach significantly enhances project transparency and governance efficiency by synchronizing schedule compliance, material integrity, and spatial accuracy into a unified digital workflow.

4. Risk Identification and Assessment Models

4.1. Analysis of Primary Risk Categories

4.1.1. Quality Risks

In high-end club renovation projects, craftsmanship defects directly compromise project quality and client satisfaction, that manifested as aesthetic inconsistencies from stone material color variations or structural stability hazards caused by uneven woodwork joints. For example, mismatched marble slabs in prominent lobby areas can disrupt visual harmony, while poorly fitted timber joints in custom millwork may loosen over time, risking structural integrity. Concealed works deficiencies pose greater latent threats such as MEP (Mechanical, Electrical, and Plumbing) leakage, and would probably leads to wall mold growth or electrical short circuits, with rework costs reaching 20% - 30% of original construction value.

These hidden failures often surface months after project completion, potentially forcing operational shutdowns for repairs. Such risks predominantly stem from deviations in construction standard implementation or inspection protocol oversights during critical phases like waterproofing or electrical rough-ins. To effectively mitigate occurrence probability, implementing end-to-end quality traceability mechanisms, such as digital sign-offs for each inspection checkpoint and embedded RFID tags in key components is essential. This ensures accountability across all trades and enables rapid defect root-cause analysis [5]. Proactive material batch-matching protocols and mandatory mock-up approvals further prevent aesthetic defects before full-scale installation begins.

4.1.2. Safety Risks

High-altitude operations during ceiling installations necessitate frequent use of mobile scaffolding and elevating work platforms, increasing personnel fall risk probability by over 35% compared to conventional construction. This risk amplification stems from constant equipment repositioning and confined maneuvering spaces characteristic of club renovations. Concurrently, improper operation of specialized installation equipment significantly heightens mechanical injury hazards, particularly when workers interface with complex decorative assemblies [6].

Material-related fire risks are critically amplified by suboptimal decorative selections: combustible materials like wood veneers and carpets failing to meet Class A fire-rating standards may elevate fire load density 2-3 times beyond permissible thresholds. When compounded by high occupant density in club venues that often exceeding 1 person per 2 m² during peak hours, and potential accident consequences escalate exponentially due to rapid smoke propagation and constrained egress paths. These compound risks mandate implementation of dynamic assessment models that continuously integrate material combustion performance data such as flame spread indices with real-time operational environment parameters like occupant counts and ventilation status. Such integrated monitoring enables predictive safety alerts through automated hazard forecasting, allowing preemptive interventions before critical thresholds are breached.

4.2. Application of Risk Assessment Methods

4.2.1. Quantitative Risk Matrix Analysis

Risk prioritization in high-end renovation projects utilizes a Probability-Impact (P-I) Matrix to objectively classify risks through quantified assessment of likelihood and consequence severity. This method assigns numerical values (1 to 5 scales) to both dimensions, then calculates composite scores to determine risk levels. For instance, material delivery delays with a 20% occurrence probability causing 5 days schedule delays and 8% cost overruns would score “medium-high” on the matrix.

This quantitative approach automatically triggers predefined contingency protocols, such as activating alternative suppliers or expedited logistics when thresholds are breached. By replacing subjective judgments with standardized scoring criteria, the matrix establishes an auditable decision framework. Project managers leverage these outputs to implement tiered resource allocation: high-scoring risks receive immediate mitigation budgets and specialized teams, while medium risks undergo biweekly monitoring. The system further integrates with project controls software to visualize risk evolution dynamically, enabling proactive adjustments before issues escalate. This systematic approach ensures evidence-based risk governance while optimizing preventive resource deployment across all project phases.

4.2.2. Monte Carlo Simulation Forecasting

Monte Carlo simulation models critical uncertainty variables which includes construction efficiency fluctuations, material supply disruptions, and labor productivity variations, through extensive random sampling. This computational method generates probability distributions for potential schedule delays and cost overruns by processing thousands of stochastic scenarios. Essential input parameters encompass historical schedule deviation rates, resource availability probabilities, and change order frequencies documented in project archives.

After executing 10,000+ iterative computations, the simulation quantifies risk exposure through precise probabilistic outcomes: for instance, identifying a 12% probability of schedule delays exceeding 10 days and a 9% probability of cost overruns surpassing 15% of baseline budgets. These statistically validated projections empower project managers to implement dynamic construction plan adjustments, such as resequencing non-critical path activities or reallocating resources. Concurrently, the methodology establishes scientifically calibrated cost buffer zones proportionate to identified risk magnitudes. By transforming qualitative uncertainties into quantifiable risk profiles, this approach significantly enhances predictive capabilities for contingency planning while introducing rigorous objectivity to risk response strategies across all project phases.

5. Risk Prevention Strategies and Implementation Pathways

5.1. Quality Risk Prevention

5.1.1. Process Standardization Development

Establish a standardized construction methodology repository covering critical processes such as stone dry-hanging and wood joinery, defining construction workflows and technical parameters. Ensure process implementation through 3D animation demonstrations and on-site practical training [7]. Implement a “prototype-first approach” by creating physical or virtual model rooms before construction. Commence batch construction only after client confirmation of key elements including texture coordination and joint detailing, thereby preventing large-scale rework. Integrate the standardization system with a dynamic feedback mechanism to continuously refine process standards, ensuring adaptation to new materials and evolving design trends.

5.1.2. Whole-process Quality Monitoring

Introduce third-party testing agencies to conduct professional evaluations of latent indicators such as air quality and sound insulation performance, ensuring compliance with high-end club acceptance standards for environmental and functional requirements [8]. Deploy an AI visual inspection system that captures construction surface images through high-definition cameras, utilizing deep learning algorithms to automatically identify defects including wall flatness deviations exceeding 2 mm and hollow tile rates surpassing 5%. This technology generates real-time rectification lists, reducing manual sampling frequency by 60% while maintaining defect omission rates below 1%, thereby establishing a closed-loop “detection-feedback-correction” control chain.

5.2. Safety Risk Prevention

5.2.1. Dynamic Safety Management System

Through deploying a network of IoT sensors to continuously monitor hazardous sources, including combustible gas concentrations and scaffolding inclination angles, the system automatically triggers site-wide audiovisual alarms within 2 seconds of threshold exceedance, reducing incident response time to under 30 seconds. Real-time data streams to centralized dashboards enable safety officers to pinpoint hazard locations and dispatch responders. Simultaneously, the integrated VR simulation system generates hyper-realistic safety training scenarios replicating high-risk situations like falls from elevation and machinery entanglement.

Workers undergo mandatory immersive training modules with pressure-sensitive feedback mechanisms, mastering emergency response protocols through repetitive scenario drills. Quarterly refresher courses incorporate updated risk patterns identified from near-miss reporting systems. Post-training competency assessments consistently achieve pass rates exceeding 95%, with skill retention verified through unannounced field simulations. This dual technological approach with combining real-time hazard interception with procedural muscle memory development, that significantly mitigates human operational errors by addressing both environmental risks and behavioral factors. Sensor calibration checks and VR content updates during monthly safety audits maintain system reliability across all project phases.

5.2.2. Emergency Plan Optimization

Regularly conduct multi-scenario emergency drills based on fire load density and personnel flow patterns, with focused evaluation of evacuation route efficiency and firefighting system coordination. Post-drill reviews leverage digital twin technology to reconstruct incident response sequences and systematically refine emergency procedures. Simultaneously, establish a tiered backup supplier registry system for critical construction materials through pre-qualification of 3–5 certified vendors.

This framework ensures rapid activation of alternative sourcing solutions within 48 hours upon primary supply failure. The integrated approach significantly compresses procurement cycles to 60% of standard duration while minimizing potential project delays. Digital twin simulations further validate optimized response protocols during quarterly emergency rehearsals, enhancing operational readiness across all risk scenarios. Continuous refinement of supplier performance criteria maintains system resilience against supply chain disruptions, ensuring consistent alignment with project safety and timeline objectives.

5.3. Contract and Cost Risk Control

5.3.1. Refined Contract Clause Design

Contracts must explicitly define pricing mechanisms for design modifications, mandating that new work items adopt either current industry benchmark rates for example, the RSMeans data or mutually negotiated pricing to eliminate valuation ambiguities and prevent disputes [9]. The implementation of a progressive performance bond release system is critical as this structured approach returns bond portions incrementally upon completion of predefined milestones like concealed work sign-offs or final inspections, creating continuous financial incentives for contractor compliance.

Concurrently, comprehensive force majeure clauses should delineate precise liability boundaries and compensation standards for events including extreme weather, supply chain disruptions, or regulatory changes. To further enhance enforceability, integrate liquidated damages provisions specifying daily penalty rates (typically 0.05-0.1% of contract value) for critical path delays, while establishing clear change order approval workflows requiring dual client-contractor authorization within 48 hours. Digital contract platforms with blockchain verification can automate milestone validations and payment releases, reducing administrative delays by 30 - 40%. Regular contract audits during monthly project reviews ensure alignment with evolving site conditions and regulatory requirements, effectively minimizing legal exposure while fostering collaborative risk-sharing partnerships.

5.3.2. Cost Dynamic Alert Mechanism

The BIM 5D platform integrates real-time quantity, schedule, and cost metrics to enable continuous budget-actual expenditure tracking. Automated alerts trigger through multiple channels (project dashboards/SMS/email) when critical thresholds are breached, specifically material waste > 5% or labor cost deviations > 3%. For high-volatility materials like structural steel and electrical copper, a dual-track procurement strategy is deployed: futures contracts secure baseline costs 3 - 6 months ahead, while daily spot market differential analysis (monitoring basis risk between futures and physical prices) dynamically adjusts order timing and volumes.

This approach maintains material cost fluctuations within ± 2% through tactical responses: strategic stockpiling during price dips and just-in-time purchasing during downward trends. Simultaneously, AI-powered variance diagnostics pinpoint cost overrun root causes, whether from design revisions, productivity gaps, or supplier defaults, enabling corrective actions within 24 hours. The system further optimizes cash flow by aligning supplier payments with project milestone completions, reducing working capital requirements by 15 - 20%. Collectively, these measures lower budget overrun risks by 35 - 40% while improving capital turnover efficiency through data-driven decision cycles [10].

5. Conclusion

In high-end club renovation projects, refined management achieves quality control through closed-loop processes spanning design, construction, and handover. Core elements include BIM-driven spatial optimization, milestone-based scheduling, and transparent material traceability systems. The risk prevention framework was supported by standardized construction methods, dynamic risk assessment models, and AI visual inspection, forming a complete chain from risk identification to emergency response.

Future development focuses on intelligent and sustainable solutions in AI-powered smart construction sites integrate robotic systems, real-time defect detection, and digital twins capable to enhance efficiency and precision; innovations in low-carbon materials require breakthroughs in bamboo fiber composites and photocatalytic coatings, coupled with lifecycle carbon assessment models to drive green transformation. Emerging applications like blockchain for contract compliance and supply chain traceability, along with VR/AR-enhanced safety training, will fundamentally reshape management paradigms and risk control boundaries in premium renovation engineering.

Disclosure statement

The authors declare no conflict of interest.

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BIM-based Construction Collision Detection and Pipeline Comprehensive Optimization

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Abstract: This paper explores the application of Building Information Modeling (BIM) technology in pipeline collision detection and optimization for a station and operation section project of Line 2 in a specific city. By leveraging BIM for 3D modeling, the study facilitates the identification of pipeline conflicts, enabling comprehensive optimization of the pipeline layout. Navisworks software is used for visualizing the model, providing an intuitive platform for detecting clashes and refining the pipeline design. The proposed BIM-based approach not only enhances construction efficiency by reducing rework and conflicts but also improves project quality through more accurate, coordinated designs. While the focus is on the construction industry, the methods discussed are applicable to various fields, offering broader potential for improving integration and efficiency in other types of construction projects.

Keywords: BIM; Collision detection; Pipeline optimization

Online publication: 4th September 2025

1. Introduction

1.1. Background

With the advent of the information age, BIM technology has gradually gained widespread attention. BIM is actually an information system that integrates various information such as buildings, city planning, environment, and human behavior based on a three-dimensional digital model. In the construction phase, the amount of field data is huge. How to effectively utilize it and achieve efficient collaboration among multiple professions has become one of the challenges faced by the current engineering industry.

Currently, scholars at home and abroad have conducted a lot of research work on BIM technology. Starting from the concept and definition of BIM, domestic scholars mainly focus on BIM application methods, BIM technical standards, BIM model optimization design, BIM technology application in construction simulation, and construction management and project delivery control based on BIM technology. Studies mainly focus on the value of BIM, modeling steps, collision detection algorithms, application effect evaluation, and the understanding and adoption of BIM technology by construction industry enterprises. At the same time, based on the above theoretical research results, many excellent cases have emerged in engineering practice. Among them, previous study analyzed the collision problems in the building information model and verified the effectiveness of the technology in solving pipeline conflicts through specific examples [1]. Fu Zi'an proposed a BIM pipeline comprehensive visualization design platform based on mobile terminals, which solves the problems of easy errors and inability to accurately reflect the actual spatial layout in the traditional pipeline drawing process [2]. Li Peng et al. developed a software for rapidly generating internal pipelines of buildings based on the building information model platform [3]. Li Minghao adopted computer vision technology to obtain three-dimensional contour data of objects through depth cameras, thereby detecting whether the pipeline layout in the building is reasonable [4], realizing the digitization of the construction process and improving construction efficiency.

1.2. Project overview

The project is located at a station and operating section of Line 2 in a certain city, with a building area of 208,000 square meters. It includes an underground station for the transfer between Line 1 and Line 2, post-station line sections, and a parking lot. The total length is 1,647 m, including two double-track tunnels (Type A), one single-track tunnel (Type B), and an underground station. This project requires the use of BIM software Navisworks for pipeline management and optimization. In traditional construction, untimely and inaccurate information communication between various professionals often leads to pipeline collisions. Taking this project as an example, there are 93 types of pipeline drawings completed during the design phase, including 50 tunnel segment pipeline layout drawings, 33 water supply and drainage pipeline network drawings, 24 integrated drawings, 18 structural construction drawings, and 21 steel component and curtain wall construction drawings. In addition, there are other auxiliary drawings. Since designers from various professions use CAD drawings, the information on the drawings is not effectively utilized, and real-time data updates cannot be achieved.

Therefore, when the project enters the implementation phase, many problems are found on the construction site, such as incorrect construction sequence, missing pipelines, repeated installation, and inconsistent pipeline sizes, which affect the on-site construction progress and cause unnecessary economic losses. According to the owner's requirements, all pipeline positioning and installation work must be completed within one month. Therefore, the effective use of BIM technology during project implementation can greatly improve efficiency. However, due to the lack of unified design standards among various professions and the use of different construction specifications by various units, the result is that the pipeline location, direction, quantity, and other information expressed in the design drawings would be chaotic, which brings great difficulties to later construction.

2. Materials and methods

2.1. BIM-based construction collision detection and integrated pipeline optimization

2.1.1. Construction requirements

Firstly, a unified pipeline database was established to enable data from various professions to be correlated, facilitating easy access and maintenance. Before construction, the design department uploaded the design drawings of each profession to the project collaboration platform and distributed them to all participants, allowing relevant personnel to view the project overview in a timely manner and understand the overall situation of the project. The construction party then organized relevant personnel to review these drawings, checking for omissions, errors, or unreasonable areas, and made timely corrections. Additionally, regular training was provided to designers from various professions to familiarize them with various standards and specifications, and to help them master advanced construction techniques, thereby improving construction quality and efficiency.

Secondly, conduct sufficient research on the construction site to clarify information such as the construction scope, length, elevation, and depth of burial for various pipelines, and develop a detailed "Integrated Pipeline Layout Plan". This plan has listed various pipeline types, specifications, lengths, materials, diameters, elevations, and other information. This could greatly reduce potential errors made by on-site construction workers during operations. Additionally, before actual construction begins, all of the starting and ending points pipelines was determined to avoid pipeline collision.

The pipeline laying stage is a critical and challenging part of the entire construction process. To avoid rework due to improper pipeline laying, aside from preparing well in the early stages, it would be necessary to take measures to ensure the accuracy of pipeline layout. For instance, during on-site construction, the construction leader should strictly follow the "Integrated Pipeline Layout Table" to ensure that each pipeline is laid in the specified position. If any issues are found, construction should be immediately stopped, and the position should be readjusted.

Lastly, to better achieve integrated pipeline optimization, BIM software was utilized for modeling and simulating the construction process. Through analyzing the model, one can intuitively understand the on-site construction situation, promptly identify potential problems, and make corresponding adjustments. Simultaneously, 3D animation was employed to showcase the entire construction process to the owners, providing them with a comprehensive understanding of the project's progress and enhancing their trust in the construction plan.

2.2. Basic process of integrated pipeline optimization

The pipeline design stage is a crucial phase of construction design. Based on different engineering characteristics and equipment features, comprehensive pipeline analysis and optimization across various specialties are required to achieve the best overall layout for the project. Currently, commonly used methods in domestic engineering practice include manual coordination, mechanical assistance, and software assistance. However, these methods often suffer from issues such as low efficiency, inaccurate results, and high costs [5].

This article analyzes the technical route of integrated pipeline optimization based on BIM: Firstly, Revit software was used to establish a construction BIM model and a site layout diagram was created based on it. Then, professional models such as architecture, structure, water supply and drainage, and firefighting was integrated into a unified platform to generate a general site plan [6]. Afterwards, integrated pipeline optimization plans were developed for various professional areas based on the site plan and integrated pipeline diagram. BIMsight software was utilized to establish a collision detection database and detect collision points. Finally, through secondary optimization and adjustment of the plan, the pipeline layout was completed.

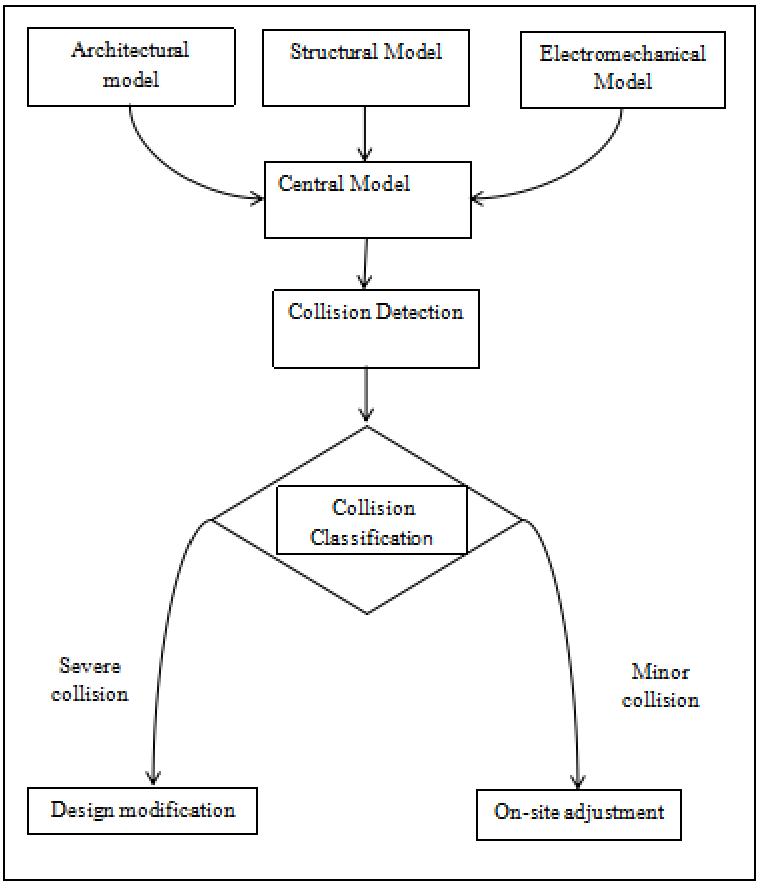

Figure 1. Basic Process of Integrated Pipeline Optimization.

The specific process was shown in **Figure 1**. This process has the following advantages: Firstly, it fully considers the architectural space layout and achieves collaborative work among various professions [7]; secondly, collision detection analysis can quickly locate collision areas, reducing unnecessary rework and modifications; thirdly, utilizing the optimized pipeline scheme can greatly reduce the difficulty of on-site implementation.

2.3. 3D model establishment

Before project implementation, a three-dimensional space coordinate system of the model was determined based on the actual situation of the project, providing precise reference coordinates for later pipeline optimization work.

When establishing a 3D model in Revit 2020 software, the following aspects was noted: (1) The model size should be consistent with the design drawings. For example, if the cable pipe specifications are marked on the design drawings, corresponding changes should be made in the model; (2) The material information in the model should be consistent with the design drawings to avoid problems such as material specification mismatches or inability to make changes; (3) For local components within the building plane, it is recommended to group them according to certain rules for easier viewing later; (4) Temporary facilities, tower cranes, etc., during construction should be modeled according to design requirements and numbered for easier drawing updates later [8]; (5) All independent pipelines, air ducts, hoods, and other components should be modeled separately for later merging; (6) For small-sized pipeline supports, bridges, and other components that do not affect the overall design, they can be directly inserted into the model without separate modeling. Additionally, during the modeling process, it should be ensured that the created model complies with national norms and acceptance standards.

2.4. Construction scheme design and optimization

According to the design drawings, the integrated pipelines of the project include sewage, water supply, firefighting, strong electricity, and weak electricity. Among them, sewage includes reclaimed water, rainwater, and sewage; water supply includes domestic water supply, production water, fire water supply, air conditioning chilled water, process water. For instance, firefighting includes fire hydrants, sprinkler systems, automatic fire alarm and automatic fire extinguishing systems, and more [9]; strong electricity includes power cables, lighting power sources, signal power sources, track circuits and others; weak electricity includes video monitoring systems, broadcasting systems, access control systems, computer network systems, telephone systems and more. During the construction process, due to lack of communication among various professions and unfamiliarity with the drawing content, on-site construction workers only follow their experience, resulting in many pipeline collisions or conflicts.

Therefore, before construction, BIM modeling of the construction project should be carried out, relevant information should be imported into the model, and a BIM model database should be established. Utilizing BIM technology can effectively improve design efficiency and the accuracy of pipeline collision detection, while also saving a lot of time.

2.4.1. Pipeline layout

After the completion of the architectural construction drawings, the pipeline layout drawings were reviewed. Due to the abundance of pipeline information, calculating and reviewing using traditional two-dimensional drawings were time-consuming, laborious, and prone to omissions or errors. Therefore, it is necessary to input the pipeline data into a BIM model and use Revit software for modeling and visualization.

Firstly, based on the pipeline layout principles, the direction and location of each layer of pipelines are determined. Secondly, according to regulatory requirements, appropriate pipeline types and materials are selected, and the pipelines are numbered [10]. Finally, parameters such as the elevation and slope of the pipelines are adjusted according to the needs of different professions. For some special pipelines, such as fire sprinkler pipes, smoke exhaust pipes, and supply and exhaust pipes, separate models need to be established. Additionally, for rainwater pipelines in underground spaces, due to limited site conditions, open excavation cannot be used for construction, and only underground excavation can be adopted. In this process, the positional relationship between pipelines must be considered to ensure that they do not affect subsequent construction processes.

2.4.2. Pipeline connection

In this study, the main equipment such as central air conditioning units, fan coil units, chilled water units, water pumps, and cooling towers was installed. Due to the numerous equipment pipelines and the fact that some equipment cannot share pipelines with other equipment, pipeline connections need to be made during construction. Before deepening the BIM model design on site, the connection scheme was the first step is to optimize to ensure that there are no duplications or omissions during construction, making the overall pipeline layout reasonable and aesthetically pleasing. By establishing a three-dimensional model of the entire building using BIM software, the layout of various equipment pipelines was combined with drawing requirements, which would be better adhere and control the positional relationship between the pipelines of various professions, achieve visual pipeline management, and discover and address crossing pipelines and collision points in a timely manner, improving construction efficiency. Meanwhile, pipeline layout at various stages was also optimized by using BIM software to avoid pipeline conflicts, improve construction efficiency, shorten the construction period, and provide support for later operation and maintenance [11].

During the construction process of this project, BIM technology was adopted to solve pipeline layout issues before construction design. Then, the Revit MEP function was used to perform precise modeling and spatial relationship analysis on the corresponding pipelines to determine the best construction plan. Based on the direction and placement of the pipelines, some obstacle areas can be effectively avoided, reducing construction difficulty, speeding up construction progress, and improving project quality.

3. Results

3.1. Collision analysis

Based on the BIM model established above, the architectural and structural components were integrated through Revit, and collision detection was performed on the integrated piping model using Navisworks.

For projects with a building height below 40 m, no underground structure, regular floor plans, and a small number and variety of pipelines, the use of Revit software combined with CAD software has already achieve relatively precise pipeline layout. However, when the building height exceeds 45 m and there is an underground structure, due to the complexity of the architectural plan and the dense piping, especially when construction workers use 2D drawings to coordinate with site conditions, it often leads to significant discrepancies between the actual piping layout and the drawings, resulting in rework.

3.2. Navisworks

To address this issue, the 3D piping model was imported into Navisworks for collision analysis. Both hard and soft collision rules could be applied to meet different construction requirements in Navisworks. Secondly, through Navisworks' visual collision report analysis table, quick queries of collision relationships between pipelines were achieved. Thirdly, by analyzing the collision results, reasonable optimization locations for the pipelines were determined. Finally, the comprehensive optimization layout of the pipelines was completed through adjusting the optimization locations, and 2D construction drawings which contain spatial information of the pipelines were suitable for the usage habits of site construction workers, was the output.

4. Conclusion

In this paper, BIM technology was adopted for collision detection of pipelines. By establishing a BIM model and combining it with Navisworks software, the 3D piping diagram is converted into a 2D detailed construction drawing. Firstly, piping space planning is carried out, and then components are created using 3D modeling software and imported into the BIM model to enable collision analysis and optimized layout of the pipelines. This method overcomes the disadvantages of long duration and low efficiency of manual measurement in traditional methods. It not only improves the accuracy of pipeline layout but also significantly reduces the rework costs caused by non-standard construction in the later stages. It enables site construction workers to visually understand the pipeline layout, avoiding issues such as errors, omissions, and collisions, thereby improving construction quality. Simultaneously, by sharing BIM model information with other construction units and design institutes, communication efficiency can be effectively improved, and project progress can be accelerated. The results can be applied to other construction fields, providing a reference for future promotion and application in more engineering projects.

Disclosure statement

The author declares no conflict of interest.

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Construction Process of Basement Floor Slab in Building Engineering Construction

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Abstract: The basement was located at the bottom of the building, which not only affected the quality of the whole construction project but also had special requirements for construction technology and construction requirements. In modern times, with the increasing height of the building, the pressure on the ground has grown, and the demands for basements in construction projects have also steadily increased. With the development of modern technology, various construction techniques for basements emerged within the construction industry. Thus, this paper analyses the type of basement floor construction technologies, highlighting the application of these methods, and points out critical issues to consider. By examining frequent basement leakage problems, the paper proposed several measures to improve the quality if basement construction, aiming to better protect the service life of the building and further improve overall quality, and offering valuable insights for future projects.

Keywords: Construction engineering; Basement slab construction; Building life span

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1. Introduction

1.1. Background

In recent years, due to the shortage of urban land resources in China and to better utilize spatial resources, relevant departments have begun to expand buildings to higher altitudes and also to underground areas. Meanwhile, the construction technology of basement floor is becoming increasingly common [1]. However, there are still some obstacles in the field of basement engineering that may affect the quality and lifespan of the building, such as concrete floor cracking and groundwater leakage in the basement, which these may potentially affects the safety and quality of the basement and even the safety of the building. Therefore, it would be significance to conduct research on the construction technology of basement floor during the construction process of building engineering.

1.2. Overview of structural design difficulties in basement engineering

The difficulties in basement structure design can be divided into many aspects. For instance, when designing a basement structure, technicians need to analyze its fire prevention and usage functions, as well as analyze it based on human factors. A brief analysis of a case study of a commercial complex basement in China reveals that the main difficulty lies in the fact that the complex is located in a bustling area with dense surrounding buildings and complex underground pipelines, which poses great challenges to the excavation and support of the basement. Therefore, designers need to accurately calculate soil pressure, choose appropriate support methods, and ensure the safety of surrounding buildings and pipelines. In addition, the waterproofing requirements for the basement are high, and the groundwater level in the area is relatively high. Once the waterproofing treatment is improper, it is easy to cause leakage and affect the functionality of the basement. Therefore, high-quality waterproof materials should be considered in the design, and waterproof structures should be designed reasonably. In addition, ventilation and lighting in the basement are also one of the difficulties. In order to meet the usage requirements, designers were required to arrange ventilation ducts and lighting wells effectively, while ensuring that the structural stability of the basement is not affected.

Overall, these design difficulties and issues can be summarized as: structural plane design, seismic design and exterior wall structure design, basement anti floating and anti-seepage design, etc. It can be said that the difficulty of basement structure design is quite complex, and relevant departments need to continuously optimize the construction technology of basement floor in order to effectively ensure the balance of basement construction and thus ensure the construction quality and service life of the entire building [2].

2. Basic procedures for bottom plate operations in basement structures

2.1. Carry out measurement and leveling work

The measurement and leveling work are conducted to ensure the accuracy and rationality of the bottom plate operation, which is the focus of the entire basement structure work. Technicians need to ensure the accuracy and precision of leveling and laying work through clear technical indicators and specific parameters, effectively avoiding omissions and defects. In the actual operation process, technicians must strictly follow the established technical indicators and parameters for the operation, and repeatedly check the measurement results. In the actual operation process, strictly follow the established technical indicators and parameters for the operation, and repeatedly check the measurement results. At the same time, technicians should establish an effective quality inspection mechanism to comprehensively inspect and supervise the leveling and laying work. Once problems are identified, timely rectification should be carried out to ensure the smooth progress of basement structure construction.

2.2. Foundation excavation

Excavation of the foundation is the key point in the construction process of the entire modern underground space structure system. Excavation of the foundation not only ensures the basic work quality and construction efficiency of the entire building, but also affects the safety of the entire underground space structure. Construction personnels are required to attach great importance to the entire process and operation procedures of foundation excavation, and integrate management with preliminary data, information materials, data mining, and basic operation procedures. Comprehensive attention should be paid to the problems in the entire foundation excavation process to ensure construction safety and quality [2].

2.3. Bottom plate brick masonry and pouring operation

The bottom brick masonry and pouring operation require technical personnel to rely on brick masonry construction technology to effectively clarify the entire operation process. During the concrete pouring process, it is necessary to form a pouring foundation pit structure and a sturdy bottom cushion layer to ensure the sequence of the entire construction process. The construction personnel should strictly follow the construction process, first excavating and cleaning the foundation pit to ensure that the size and depth of the pit meet the design requirements. Then, the bottom cushion layer was laied using high-quality materials to ensure the firmness and stability of the cushion layer. When pouring concrete, technicians need to pay attention to control the speed and sequence of pouring to ensure that the concrete can evenly fill the foundation pit and avoid voids and cracks. By ensuring the sequence of the entire construction process is accurately obey, the quality of the bottom brick masonry and pouring operations would be guaranteed, which lays a solid foundation for the smooth progress of the construction project [4].

2.4. Construction of waterproof layer structure

The construction of waterproof layer structure is a key point in the construction process of basement space. Technical personnels are required to clarify the construction process and procedures of waterproof layer structure. The density and strength of the bottom plate structure should be analyzed as important indicators. In the bottom plate operation, steel reinforcement structure should be used to improve the anti-seepage performance of the bottom plate structure. At the same time, relevant departments should also emphasize further optimization of the external wall construction process.

2.5. Timely carry out maintenance work

During the construction process of the bottom plate, maintenance work should be carried out by technicians in a timely manner, strengthen the analysis of the characteristics of the concrete structure itself, enhance the maintenance and curing operations of the structure, ensure the stability of the concrete performance, and at the same time, technicians need to improve the performance indicators and quality of the concrete structure to ensure the stability of the entire bottom plate construction process. At the same time, construction personnel should pay attention to the entire construction process, timely improve and optimize the maintenance management work, and ensure that various maintenance measures can be effectively implemented [5].

3. Countermeasures for improving the construction level of the bottom plate

3.1. Reasonable selection of waterproof materials

One of the keys to improving the construction level of the bottom plate is to choose waterproof materials reasonably. The quality of waterproof materials directly affects the waterproof performance of the basement floor, which in turn relates to the service life and safety of the entire building. When choosing waterproof materials, technicians should first fully consider the usage environment and engineering requirements of the basement. For example, in areas with high groundwater levels, waterproof materials with good impermeability properties should be selected. Polymer waterproofing membrane is a commonly used high-quality waterproofing material, which has advantages such as high tensile strength, corrosion resistance, and aging resistance. For example, in a large commercial complex project, due to its location in an area with a high groundwater level, the construction party conducted multiple investigations and comparisons, and ultimately chose polymer waterproofing membranes. During the construction process, the laying and welding were strictly carried out in accordance with the specifications, ensuring a tight connection between the rolls and effectively preventing the infiltration of groundwater [6]. Meanwhile, waterproof coating is also an important waterproof material. Different types of waterproof coatings are suitable for different engineering situations. For example, cement-based permeable crystalline waterproof coatings forms crystals inside concrete, block capillary channels, and improve the impermeability of concrete. In the construction of the basement floor in a residential community, the construction party applied a layer of cement-based permeable crystalline waterproof coating before pouring the concrete, which not only improved the waterproof effect but also enhanced the durability of the concrete. In the process of basement floor work, leakage problems often occur due to the reverse selection method and serious quality problems of the materials themselves. For example, many waterproof materials cannot meet the requirements and construction standards of the basement waterproof layer structure, which can cause leakage problems. Relevant departments need to effectively select and test the performance of waterproof materials before the construction project, avoid the occurrence of unqualified materials, and effectively grasp the quality concept of materials.

At the same time, technical personnel should also pay special attention to the storage and maintenance of waterproof materials during the construction process, adopt scientific and reasonable protection and management measures, ensure the performance and quality of materials, maintain normal and stable states, and avoid interference from external adverse factors.

3.2. Carry out concrete waterproofing construction well

Concrete waterproofing construction refers to the process of requiring relevant departments to optimize the impermeability of waterproof concrete, control the amount of cement in concrete, and select appropriate cement dosage and standards. While ensuring the strength of concrete, the sand ratio should be controlled, and the index of phosphorus content in concrete sand should be effectively utilized to carry out waterproofing operations of construction joints. At the same time, scientific and reasonable pouring methods should be adopted to complete construction tasks and improve the waterproof performance of concrete structures [7].

3.3. Use polymer waterproof materials for construction

During the construction process of the basement floor in building engineering, technicians should use polymer waterproof materials for construction. At the same time, they should carefully clean the dust and debris on the base layer to ensure the use of polymer cement and waterproof bonding materials, and ensure that the bonding thickness is controlled within a certain range. In the construction of basement floor, technicians need to control the structural floor cushion layer well. For example, the concrete part can be fully bonded to carry out the construction of the roof and exterior walls, and the side walls can be constructed using various methods of connection to avoid sliding and leakage problems [8].

3.4. Strengthen the training of construction process personnel

During the entire basement floor construction process, the quality of construction affects the stability and safety of the entire building. Therefore, it is crucial to provide professional and effective training for construction personnel. Firstly, theoretical knowledge training should be provided to construction public welfare personnel, and experienced engineers or technical experts should be hired as lecturers to explain the process, technical points, and quality standards of basement floor construction. Through the presentation of illustrated courseware, it is ensured that construction personnel have a clear understanding of the bottom plate construction. At the same time, basement waterproofing engineering should be explained, and the selection of waterproofing materials, construction methods, and common leakage problems should be analyzed and dealt with to help construction personnel effectively solve related problems in the construction of basement bottom plates in different projects. For example, relevant departments can analyze cases of bottom plate cracks caused by improper concrete pouring in a certain project, summarize experience and lessons, and ensure that construction personnel have a clear understanding of the importance of concrete pouring technology and maintenance methods. Secondly, technicians need to enhance their practical and technical skills. At the construction site, technicians can conduct practical demonstrations, demonstrating key operation methods and precautions such as the installation of steel bar binding templates and concrete pouring, to ensure that construction process personnel observe and learn up close. By asking questions and receiving answers, they can further shorten their time and operational level.

In addition, simulation exercises can also be used to effectively deal with basement floor construction problems and emergencies under different construction conditions, ensuring that construction personnel can handle emergency situations, such as power outages and equipment failures that occur during the simulated concrete pouring process, testing the construction personnel's ability to respond and team collaboration [9]. Finally, it is necessary to conduct regular assessments and evaluations for construction personnel. Professional performance evaluation systems and platforms can be introduced to encourage technical personnel to continuously improve themselves through analysis and statistical analysis of their work situation and quality. In addition, theoretical knowledge exams can also be conducted to test the mastery of basement floor construction technology by construction personnel. Through training on key technical points, quality standards, safety regulations, and other aspects of the process flow, construction personnel can be classified and managed in a timely manner. For those who achieve excellent results, rewards should be given; For personnel whose grades do not meet the standards, targeted coaching and retraining should be provided. The relevant departments need to regularly assess the actual operational ability of construction technology personnel, requiring them to complete operational tasks within the specified time. For example, by analyzing the situation of steel bar binding, formwork installation, and concrete pouring, the construction quality and efficiency of the assessment personnel should be scored in a timely manner, and salaries should be paid based on the scores. Construction personnel should be encouraged to make progress in a timely manner, and their specific abilities and comprehensive levels should be evaluated regularly [10].

4. Conclusion

In summary, as an important component of a building, the construction quality of the basement directly affects the quality and service life of the entire construction project. The construction technology of basement floor plays an important role in the construction industry. Through in-depth analysis, this article clarifies the precautions that need to be taken during the construction process, as well as multiple measures to deal with leakage problems. In the construction of basement floor, relevant departments should strictly follow the construction process requirements, from material selection, construction process control to quality inspection, and all aspects should be rigorous and meticulous. Attention should be paid to the training and management of construction technicians, improving their professional quality and sense of responsibility, and ensuring the standardized operation of the construction process. At the same time, it is necessary to continuously strengthen the research and application of modern construction technology, innovate construction methods and processes based on actual engineering situations, and improve the efficiency and quality of basement floor construction.

Disclosure statement

The author declares no conflict of interest.

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"Bridging the Moon with Numbers, Creating Yongle with Wisdom": Smart Technology-Driven Rural Tourism Landscape Planning - A Case Study of Yongle Village, Dongxi Town, Qijiang District

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Abstract: This study proposes solutions to address issues such as the lack of distinctive culture, inadequate architectural protection, insufficient experiential landscapes, and cultural forgetting in Yongle Village, Dongxi Town, Qijiang District. Relying on the landscape pattern of "little bridges, flowing streams, and households" and the Bayu stilted building complex in Yongle Village, the study aims to facilitate rural industrial upgrading and inject new vitality into rural revitalization through "digitalization + smart agriculture." By integrating cutting-edge technologies such as digital twins, AI, and the Internet of Things, the study constructs a system of "one brain (rural wisdom brain) and three networks (cultural perception network, ecological monitoring network, and industrial service network)" to achieve "digital cultural tourism applications + smart agriculture applications + ecological protection applications" and promote the deep integration of traditional village protection and modern technology. The study strives to create a new smart tourism model that integrates "technology empowering nostalgia, ecology, countryside, healthcare, and cultural tourism," providing a replicable and promotable example for rural revitalization.

Keywords: Technology empowered; Countryside; Ecology; Cultural tourism

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1. Introduction

1.1. Project background

As evident from relevant documents such as the "Beautiful Village Construction Guidelines" GB32000-2015, "Overall Planning of National Land Space in Chongqing (2021-2035)", "District Planning of National Land Space in Qijiang, Chongqing (2021-2035)", and "High-standard Farmland Construction Planning in Chongqing (2021-

2030)", tourism is a highly information-intensive and information-dependent industry. Information permeates the entire process of tourism activities and is the foundation for the survival and development of the tourism industry [1]. The impact of informatization on tourism development is increasingly profound, and the level of tourism informatization has become one of the important indicators of the development level of tourism destinations.

Simultaneously, with the rapid development of global tourism and continuous technological advancements, tourist demands are gradually shifting from traditional scenic spot visits to more personalized, interactive, and intelligent services. As a product of the deep integration of tourism and information technology, smart tourism has become an important force driving the transformation and upgrading of the tourism industry. Yongle Village, Dongxi Town, Qijiang District, Chongqing, is located in a scenic area with a rich cultural heritage and abundant internal and external resources, providing unique conditions for the development of smart tourism.

1.2. Design purpose

1.2.1. Achieving organic integration of technology and humanities

The innovative pathways for combining digital technology with traditional village protection was the core design objective of this project. Through intelligent technological means such as the Internet of Things, AR/VR, and digital twins, the project was aimed to activate Yongle Village's cultural heritage and natural ecological resources in a "light intervention, micro-transformation" manner. This approach has been suggested to avoid damaging the village's original texture due to technology application and achieves the sustainable development goal of "technology empowering nostalgia."

1.2.2. Constructing a new industrial model integrating agriculture, tourism, and culture

The homogenization dilemma of traditional rural tourism was the aim of this project. By utilizing a smart agriculture monitoring system, the output value of farmland was enhanced. In combination with digital cultural tourism products such as AR navigation and intangible cultural heritage workshops, an experience economy that formed a three-in-one industrial chain of "agricultural production-cultural experience-ecological tourism was created. A sustainable and self-sustaining business model for rural revitalization was provided.

1.2.3. Innovating the way of living cultural inheritance

Addressing the issue of rural cultural discontinuity, a cultural inheritance scene through digital technology was constructed in this project. The blockchain to preserve intangible cultural heritage skills was used, and AI was utilized to generate interactive print paintings, and immersive farming theaters was involved. These efforts had enabled younger generations to understand traditions through contemporary language, facilitating the creative transformation and innovative development of cultural heritages like Qijiang farmer print paintings and ancient farming methods.

1.2.4. Establishing an ecological smart management system

Balancing ecological protection and economic development was focused on in the design. By deploying an environmental sensor network, it was continuously monitored water quality, soil, and biodiversity data. This data was then converted into environmentally friendly games that tourists could participate in, such as an "ecological bank" points system. The environmental protection from government regulation was shifted in this approach to promote awareness to all citizens.

1.2.5. Providing a lightweight model for rural revitalization

A rural transformation pathway of "small team + appropriate technology" was validated in the project. Through the low-cost integration of technologies (such as offline AR and solar-powered IoT devices) by a 4-person interdisciplinary team, a replicable digital transformation solution for resource-limited villages was provided. This has demonstrated how to achieve maximum benefits with minimal intervention.

1.3. Design significance

1.3.1. Promoting the deep integration of agriculture and intelligence, creating a new paradigm of smart agriculture

A traditional agriculture was upgraded in this project into a visual, interactive, and learnable smart agriculture system through technologies like IoT monitoring, AI data analysis, and AR interactive experiences. For example, a QR code could be scanned to view crop growth status and even participate in virtual farming games. This "production + experience + science popularization" model not only improves agricultural production efficiency but also adds touristic value to farmland, promoting the integrated development of primary, secondary, and tertiary industries.

1.3.2. Preserving and inheriting rural cultural heritage, activating new life for intangible cultural heritage

Addressing the issue of rural cultural discontinuity, digital was adopted in the project adopts to preserve and revitalize the intangible cultural heritage resources of Yongle Village. For instance, with AR Qijiang print paintings; to watch the printmaking process and engage in DIY creation, tourists could scan with their phones. These innovative approaches brought traditional culture to life and pass it down, enhancing rural cultural confidence.

1.3.3. Promoting the popularization of ecological environmental protection awareness and building a green smart village

The project has created environmental protection concepts deeply rooted in people's hearts through ecological monitoring networks and gamified interactions. For example, the "Biodiversity Bank" allows tourists to take photos and identify plants and animals, earning ecological points to redeem rewards. This "data visualization + public participation" model was transformed an abstract concept into a perceivable and actionable way of life.

1.3.4. Promoting rural revitalization and development, exploring sustainable paths to prosperity

The project not only enhances the tourist attraction of Yongle Village but also drives income growth for villagers through digital means, forming a virtuous cycle of "cultural tourism attracting visitors - agricultural value-adding - shared prosperity for villagers," providing a sustainable model for rural revitalization [2].

1.3.5. Providing new smart agriculture and learning methods, driving innovation in science education

The limitations of traditional agricultural exhibitions, creating a smart science popularization system that is "playable, learnable, and shareable" was broke through the project. A research and practice base was provided in this "experiential learning", which not only attracts family tourists for primary and secondary school students, pushing agricultural science popularization towards being more interesting and modern.

2. Market analysis

2.1. Location analysis

Yongle Village, Dongxi Town, Qijiang District, is located in the southeast direction of Chongqing's main city, approximately 15 kilometers away from the Qijiang urban area. It is situated in the golden transition zone between Chongqing and Guizhou, with significant locational advantages. The village is adjacent to the Chongqing-Guizhou Expressway and National Highway 210, with a 1.5 hours' drive to the main urban area of Chongqing, providing convenient transportation. Additionally, it neighbors Dongxi Ancient Town, a national historic and cultural site, allowing it to share its mature tourist resources. The village is situated along the banks of a tributary of the Qi River, surrounded by mountains and water, featuring typical Bashu mountainous settlement landscapes and well-preserved Ming and Qing dynasty hanging buildings. It possesses both the charm of a Jiangnan water town with "little bridges, flowing waters, and households" and the three-dimensional spatial characteristics of a mountainous village. This unique "suburban and ancient-modern fusion" location not only provides rich cultural and ecological resources for the development of rural tourism but also effectively meets the demand for leisure tourism in the Chongqing metropolitan area, giving it inherent advantages for the development of smart cultural tourism and ecological agriculture.

2.2. Natural conditions analysis

The region is located on the southeastern edge of the Sichuan Basin and has a typical subtropical humid monsoon climate, with an average annual temperature of 18.2 °C. It experiences abundant rainfall and distinct seasons. The village is built near mountains and rivers, with a topography mainly consisting of shallow hills ranging from 300-500 meters in elevation. A tributary of the Qi River flows through the village, forming a natural "two mountains and a valley" landscape. The vegetation coverage rate in the area is over 65%, dominated by subtropical evergreen broad-leaved forests. The surrounding area features diverse ecosystems such as terraced fields, bamboo forests, and streams. The soil is primarily purple soil and paddy soil, suitable for crop growth. This organic integration of "mountains, water, fields, and forests" not only constitutes a rich landscape resource but also provides superior environmental conditions for the development of ecological agriculture and rural tourism. Additionally, the moderate climate ensures a suitable tourism period of up to 10 months throughout the year.

2.3. Analysis of cultural resources

The area boasts a profound cultural heritage and unique folklore resources. Its cultural characteristics are mainly reflected in three aspects: Firstly, the well-preserved traditional architectural complex of Bayu, represented by the stilt houses from the Ming and Qing dynasties, whose layout following the contours of the mountains demonstrates the architectural wisdom of "harmony between nature and humanity"; secondly, the rich intangible cultural heritage, including the living cultural inheritance such as Qijiang farmer printmaking, traditional farming techniques, and folk mountain songs; thirdly, as an important node on the branch line of the Ancient Tea Horse Road, there are remains of the ancient road and memories of commercial culture. These cultural resources are organically integrated with the natural landscape of "small bridges and flowing streams" in the village, forming a unique style of "landscape as the form and culture as the soul". Among them, farmer printmaking has been listed in the Intangible Cultural Heritage of Chongqing, providing a high-quality cultural IP for the development of cultural and tourism integration. The village still retains traditional farming customs such as the 24 solar terms and folk activities such as the "New Harvest Festival", constituting a complete rural cultural ecosystem of Bayu.

2.4. Visual analysis

In terms of visuals, the area presents a visually rich and geographically distinctive landscape system: The village follows the contours of the mountains, and the cascading stilt house complex, terraced fields, bamboo forests, and streams form a vertical landscape belt of "houses-terraced fields-mountain forests", creating a highly rhythmic three-dimensional picture. The visual focus is concentrated on the winding bluestone ancient road through the village and the century-old wind and rain corridor bridge spanning the stream, where the mottled wooden frames and gurgling streams form a delightful contrast.

In summary, the region has superior comprehensive conditions for developing rural tourism. It is located close to the main city of Chongqing with convenient transportation, which can effectively meet the demand for urban leisure; it has an ecological base that integrates "mountains-water-fields-forests" with a pleasant climate and long suitable tourism period; it preserves intact cultural resources such as the Bayu stilt house complex, Qijiang farmer printmaking and other intangible skills, as well as traditional farming culture, which constitute unique selling points; and its visually cascading three-dimensional space and changing pastoral colors throughout the seasons form a strong attraction. These resource endowments highly align with the growing demand for short-distance eco-cultural tourism and immersive experiences among the urban population in Chongqing. Furthermore, the innovative application of digital technology can further enhance product differentiation and competitiveness, making the project have significant development potential and competitive advantages in the rural tourism market of the Chengdu-Chongqing region.

3. Design principles

3.1. Experiential landscape as the developmental feature

The traditional static viewing mode was broken through in the design and a participative and experiential living landscape was created through immersive interactive technology and multi-sensory experience design. Based on preserving the village's original spatial texture, interactive nodes such as AR virtual scenes, intelligent commentary systems, and farming experience areas will be implanted, enabling visitors to "touch history, experience farming, and perceive ecology." A touring system of "one step, one scene, one experience" has been formed , allowing the landscape to become a medium connecting people and culture.

3.2. Non-material cultural heritage features as auxiliary means

A dual-track strategy of digital activation and scenarized reproduction was adopted to innovatively transform intangible cultural heritage resources such as Qijiang printmaking and traditional crafts. An intangible cultural heritage AR experience hall was established, and a DIY digital workshop was developed, festival exhibition activities was planned, the intangible cultural heritage was shifted from static display to dynamic participation. Simultaneously, blockchain technology was utilized to establish a digital archive, ensuring the authenticity and sustainability of cultural inheritance.

3.3. Cultural education as the basic goal

The educational function of "learning while touring" was emphasized in this project, and a local education system was constructed covering all age groups. For children, there were nature observation trails and farming tool experience areas. For teenagers, there were STEM courses on seasonal farming. For adult visitors, A cultural decoding guidance system was provided. Through hierarchical and interesting knowledge output, the dual goals of cultural dissemination and value delivery were achieved.

3.4. Countryside practice as the core requirement

Adhering to the concept of "farmland is the classroom," the agricultural production spaces was transformed into educational practice places in this design. A participative smart farmland demonstration area was planned, where visitors claimed plots through an app, crop growth was monitored, and the entire process from seeding to harvesting was experienced. Additionally, a traditional farming experience area was set up, traditional skills like cow farming and manual harvesting was preserved, a three-dimensional scene of ancient and modern farming dialogue was created.

3.5. Safe development as the core criterion

A three-level safety guarantee system was established in this design: physically, the traditional village disaster prevention layout (such as building sites selected for mountain and flood avoidance) was retained; technically, the lightning protection and moisture-proof IoT devices was adopted; and operationally, the emergency plans and digital monitoring systems was planned. All interactive devices have passed safety certification, and children's activity areas are designed with soft pavement and no sharp corners, ensuring a safe experience for visitors of all ages.

3.6. Adaptation to local conditions as the basic premise

Following the principle of "light intervention and micro-renovation," all construction was based on existing terrain and architectural texture. Smart devices are wireless and solar-powered, reducing pipeline excavation. Local bamboo, wood, and stone materials was used in landscape sketches. The farming experience area was divided based on the original field layout, minimizing disturbance to natural ecology and village scenery, achieving harmonious coexistence between technology implantation and the local countryside.

4. Design analysis

4.1. Overview of design concept

The core design philosophy of "Enabling Nostalgia with Technology, Revitalizing Tradition with Wisdom" was adhered in this project. Through the approach of "digital weaving," modern technology was organically integrated into the natural and cultural fabric of Yongle Village [3]. Supported by the "One Brain, Three Networks" smart system, a landscape system that integrates "production, ecology, and lifestyle" was constructed, achieving immersive inheritance of intangible cultural heritage, innovative transformation of agricultural resources, and intelligent protection of the ecological environment. Ultimately, this project has aimed to create a rural revitalization demonstration model that combines the local characteristics of Bayu with the features of the digital age.

4.2. Analysis of design

A "double helix" structure was adopted in the design: longitudinally, the technical path of "cultural decoding - spatial translation - technology implantation - operational activation" was followed to complete the entire process design from resource sorting to product implementation; horizontally, the spatial strategy of "core detonation - axis series connection - regional coordination" was employed to form a three-dimensional layout of "smart hub + themed loop + functional clusters." The focus was on grasping the adaptability of traditional space to modern functions and the balance between digital experience and cultural depth, ensuring that every design decision is technically feasible and culturally reasonable.

4.3. Axis analysis

An experience axis network was constructed in the plan of "one main axis and three sub-axes": the main axis followed the ancient path and stream to form a "cultural traceability axis," connecting key nodes such as the digital intangible cultural heritage museum and the AR wind and rain bridge; the sub-axes include the "ecological exploration axis" (mountain forest trail + smart monitoring station), the "farming experience axis" (terraced field theater + agricultural innovation workshop), and the "rural life axis" (renovated guesthouses + digital fireplace). The axes were interconnected through a smart navigation system, forming a thematically distinct and mutually permeable tourism route system that guides visitors through a deep experience from natural cognition to cultural resonance.

5. Business model design

5.1. Self-selection digital cultural tourism products

A series of technological and cultural innovation products with local characteristics was created, mainly including:

(1) Augmented Reality Art Creation Kits (containing traditional printmaking materials and online interactive programs)

(2) Technology-enabled Agricultural and Sideline Product Kits (equipped with a full traceability system)

(3) Digital Collection Certificates (with unique digital asset value)

Establish a three-dimensional sales network of "Internet Platform + Automatic Vending Terminals", set up popular price gradients to facilitate quick on-site ordering by tourists, and optimize the efficiency of the purchasing process.

5.2. Interactive experience service projects

A participatory tourism consumption system was established, focusing on the development of:

(1) Cloud Farm Trusteeship Services (annual subscription, providing basic planting monitoring)

(2) Traditional Handmade Experience Courses (appointment-based participatory teaching)

(3) Special Accommodation Combination Products (dynamic pricing system)

Implement a "membership fee + personalized service" charging method. For example, farm members can purchase virtual planting advisor services to cultivate stable customer relationships[4].

5.3. Education-integrated service solutions

The knowledge popularization tourism products were developed, including:

(1) Off-campus practical teaching combinations (virtual agricultural experience + outdoor practical guidance)

(2) Parent-child nature cognition activities (using interactive games on smart devices)

(3) Digital skills improvement courses for educators

Adopt an institution cooperation and profit-sharing mechanism to achieve revenue overlay from bulk purchases and individual consumption, while building a teaching user database.

5.4. Social responsibility practice plan

A new model combining business and public welfare was created:

(1) Digital protection projects for traditional skills (with partial revenue dedicated to skill inheritance)

(2) Online promotion platform for agricultural products (waiving platform fees for producers)

(3) Environmental protection and cultural innovation development plan (innovative use of traditional agricultural tools)

Establish a public welfare behavior reward mechanism where participants can obtain exclusive tourism rights through volunteer service or public welfare consumption, promoting a sustainable public welfare model.

6. Technical implementation

6.1. Project features

6.1.1. Excellent geographic location

The project was conducted in Yongle Village, Dongxi Town, Qijiang District, which was located at the junction of Chongqing and Guizhou provinces. With only a 1.5 hours' drive from the main urban area of Chongqing, providing convenient transportation and a wide radiation range for the customer market. Nestled between mountains and rivers, and adjacent to the nationally renowned historical and cultural town of Dongxi Ancient Town, the village not only shared mature tourism facilities but also retained the original style of the Bashu mountainous region, forming a composite location advantage of "suburban recreation + cultural immersion" and providing natural conditions for the development of short-distance depth tours.

6.1.2. Deep cultural heritage

The project was rooted in the well-preserved Ming and Qing dynasties hanging footbridges and Chongqing farmer's print, which are provincial intangible cultural heritages in Yongle Village. Through digital twin technology, the traditional mortise and tenon structure of the buildings was precisely recorded, and AR interaction is used to visualize the printmaking skills. Special scenes such as the "Digital Fire Pit" and "Solar Term Farming Theater" were designed to transform intangible cultures such as oral history and folk songs into experiential and transmittable live resources, building an inheritance system where "architecture was read and culture was touched."

6.1.3. Diversified educational experience

An innovative design covers an educational matrix for all ages, including an "AR Nature Detective" exploration game for children, STEM farming laboratories for teenagers, and intangible cultural heritage digital workshops for adult tourists. Through visualized farmland sensor data and traditional farming tool experience zones, immersive learning is achieved where "the field is the classroom, and the farming tools are the teaching aids," meeting differentiated needs such as study tours, family and children's activities, and silver-haired education.

6.1.4. Sustainable development

A "low-impact development" technical strategy was adopted. All smart devices are wireless and were powered by solar energy. Digital exhibition halls were transformed from abandoned farmhouses, preserving 80% of the original farmland texture. A "Village Digital Cooperative" operating model was established, training locals to serve as AR content reviewers and sensor maintainers, ensuring that the project's later operation did not rely on external teams and forming a triple sustainable mechanism of economy, ecology, and society.

6.1.5. Digital intelligence empowerment innovation

A "cultural gene intelligent matching algorithm" was utilized, where building restoration plans were automatically generated through machine learning. An "ecological data storytelling engine" has been developed to transform real-time monitoring data into AR narrative content. In particular, a UGC crowdsourcing platform has been constructed where tourist-created digital prints and farming animations, after review, the official system was integrated and a continuously growing "digital cultural gene bank" was formed by upgrading the paradigm of technology application from unilateral output to co-creation.

6.2. Innovation points

6.2.1. New applications of digital cultural tourism, and new inheritance of old culture

In response to the national strategy on cultural digitization and rural cultural revitalization policies, An entry point was taken by digital cultural tourism in the project, that was further integrated with regional cultural elements, and rural historical and cultural heritage was inherited.

6.2.2. New applications of smart agriculture, keeping pace with the times

A "cloud-edge-end" collaborative smart agriculture system was innovatively constructed, cutting-edge technologies such as 5G, AI, and blockchain was deeply integrated, and a new smart tourism model of "technology empowering nostalgia" was created.

6.2.3. New applications of intelligent monitoring, and new green ecological protection

In the project construction, environmentally friendly and energy-saving technologies such as solar power generation systems and rainwater collection and utilization systems were adopted to reduce the consumption of natural resources. At the same time, intelligent monitoring and data cloud platforms were utilized to create a green and sustainable rural tourism landscape.

6.2.4. Rural "digital-smart" tourism landscape promotes development

This project was aimed to create a "cultural-ecological-smart" collaborative development model that aligns with the requirements of industrial integration development in the national rural revitalization strategy. By developing rural tourism and agriculture, it promoted local economic growth, increases farmers' income, promoted the prosperity of rural industries and affluent living, and provided strong support for comprehensive rural revitalization.

7. Summary

This project, with Yongle Village, Dongxi Town, Qijiang District, Chongqing as the carrier, has created a demonstration model of technology-empowered rural revitalization through the innovative integration of "digital cultural tourism + smart agriculture + ecological protection". The project has fully utilized Yongle Village's ecological advantages of "mountain-water-field-forest" integration, well-preserved Bayu architectural complexes, and intangible cultural heritage resources. By applying cutting-edge technologies such as digital twins, AR/VR, and the Internet of Things, a "one-brain, three-networks" smart system has been constructed, realizing the digital transformation of traditional villages. In spatial planning, a three-dimensional network of “cultural traceability axis + ecological exploration axis + farming experience axis” has been formed, and characteristic products such as intangible cultural heritage AR activation, smart farmland monitoring, and ecological data gamification have been developed, which not only preserve the authenticity of the village but also created an immersive new experience [5]. Through the technical strategy of “light intervention and micro-renovation” and the operation mode of “villagers’ digital cooperatives”, the project has explored a sustainable path of cultural inheritance, ecological protection, and industrial revitalization, providing replicable and promotable practical experience for the digital construction of similar villages and vividly interpreting the core concept of “technology empowering nostalgia”.

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Optimization of Technical Briefing Management Process in Construction Projects

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Abstract: This paper examines the challenges in the technical briefing process for construction projects, including a three-level system and issues related to formalization. An optimization approaches was introduced based on the PDCA cycle, alongside the application of BIM and AR technologies. The key preparatory measures were outlined in this study and the functions of the management system was mentioned. Through case comparisons, this paper demonstrated that these optimizations can significantly improve efficiency and quality, support the development of an evaluation system to verify results, and highlight the critical role of organizational support.

Keywords: Construction project; Technical briefing; Process optimization

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1. Introduction

The acceleration of urbanization and consumption upgrading have propelled the real estate fine decoration project to become pivotal in enhancing building quality and meeting the demands of the high-end market. The "Guangzhou Quality Management Measures for Housing Construction and Municipal Infrastructure Engineering" has been implemented since January, 2025, clarifying the role of the construction unit as the primary responsible party for project quality and requiring the strengthening of quality control throughout the entire life cycle. Currently, fine decoration projects face challenges such as differentiated management across multiple formats, insufficient process standardization, and common quality issues like wall cracks, hollowed-out vitrified tiles, and waterproofing failures. The new policy emphasizes the utilization of digital supervision and engineering information data management systems to promote the application of BIM technology, blockchain traceability, and AI monitoring, providing support for risk assessment and dynamic prevention and control. The research focuses on formats such as office buildings, shopping malls, and high-end clubs, exploring an integrated management model of "design-construction-operation and maintenance" through updating technical standards, flexible construction organization, and legal risk hedging strategies. The aim is to provide theoretical and practical references for industry standardization and sustainable development.

2. Establishment of technical management system for fine decoration engineering

2.1. Key points of technical management in the design phase

Technical management in the design phase is the core element of quality control in fine decoration projects. The standardized design process requires clear collaboration rules among various disciplines, relying on a modular design library to achieve systematic integration of spatial functions and decorative elements. The in-depth application of BIM technology utilizes 3D model collision detection to optimize the layout of electromechanical pipelines and the finishing scheme of decorative surfaces, thereby avoiding rework risks during the construction phase. A multi-dimensional evaluation system should be established for the selection of decorative materials, comprehensively considering fire resistance, environmental protection level, and visual presentation effects, and combining physical sample testing to verify material compatibility. Environmental protection indicators should be controlled in accordance with green building standards, implementing source control for harmful substances such as formaldehyde and TVOC, and ensuring material compliance through a supply chain traceability system [1]. Design results need to be embedded into construction feasibility verification, with process and method rehearsals for complex nodes to ensure that the design scheme meets technical implementation conditions. Technical management in the design phase needs to form a closed-loop feedback mechanism, feeding construction experience back into design optimization to enhance the efficiency of technical collaboration across the entire chain.

2.2. Core of technical management during the construction phase

Technical management during the construction phase focuses on process standardization and quality traceability. Prefabricated construction technology reduces on-site wet operations through prefabricated components and modular installation, and clarifies process parameters through detailed node design to minimize human operational deviations. Concealed works undergo visual inspection and QR code traceability management to ensure verifiable quality in key processes such as waterproofing and pipeline laying. The digital management platform integrates construction progress, material mobilization, and quality inspection data, utilizing AI image recognition technology to intelligently diagnose indicators such as tile hollowing and wall flatness. Technical disclosure employs 3D animation and VR simulation to enhance operators' understanding of complex processes. Periodic technical reviews encompass material re-inspection, process compliance testing, and system joint debugging, establishing a closed-loop mechanism for addressing quality issues [2]. The entire construction process requires the establishment of a data chain to support decision-making, optimize process standards through statistical analysis of quality defects, and form a dynamic and improving technical management cycle system.

3. Differentiated management and control of multi-format fine decoration projects

3.1. Management characteristics of fine decoration of office buildings

The refined decoration of office buildings requires a balance between functional complexity and corporate brand expression, with the integration of electromechanical systems becoming a key focus of technical management. For functional composite spaces, BIM technology is needed to achieve three-dimensional coordination among strong and weak electricity, HVAC, and intelligent systems, avoiding pipeline cross-conflicts while reserving access for future operation and maintenance. Customization of corporate image requires the integration of CI logo systems in space color, material, and lighting design. Through the coordinated application of standardized modules (such as ceiling joist systems and partition systems) and customized components (such as corporate LOGO background walls), a balance between personalized needs and construction efficiency is achieved [3]. Space planning needs to incorporate a flexible expansion mechanism to meet the needs of office unit reorganization, using prefabricated partitions and integrated ceiling systems to facilitate rapid dismantling and modification. Material selection should emphasize durability and noise reduction performance, with focus on controlling the stain resistance and joint technology of decorative materials in high-frequency use areas to ensure long-term unity between function and aesthetics.

3.2. Challenges in the management of fine decoration in commercial complexes

The fine decoration of commercial complexes faces dual challenges of business diversity and dynamic tenant turnover. For the interface coordination between anchor stores and public areas, it is necessary to establish unified design guidelines, clarify standards for fire zones, electromechanical interfaces, and decorative surface finishing, and achieve seamless integration of multiple professional interfaces through the EPC model. The construction organization needs to build a dynamic progress model, adopt modular construction to address the lagging of anchor store plans, and reserve pipeline connection ports and elastic finishing schemes for decorative surfaces. Elastic construction requires the integration of BIM progress simulation and supply chain early warning systems, graded response to the personalized needs of brand shops, prioritizing the completion of structural base layers and electromechanical backbone systems, and phased delivery of terminal equipment and decorative surfaces [4]. To address the risk of business streamline adjustments, detachable metal joist systems and quick-assembly wall and floor systems are adopted to reduce the impact of later renovations on the main structure. The seamless transfer of construction data and later operation management is achieved through a digital operation and maintenance platform.

4. Engineering risk identification and assessment system

4.1. Analysis of risk sources throughout the entire life cycle

4.1.1. Quality risk: Chain reaction of material deterioration and process defects

The risk of material deterioration stems from environmental factors and supply chain fluctuations. Ultraviolet radiation and changes in temperature and humidity can lead to color differences and structural deformation in decorative materials. Accelerated aging experiments are needed to predict the performance degradation curve of materials. Process defects often have a chain reaction in concealed works, such as hollow spots and mold growth in decorative surfaces caused by poorly compacted waterproof layers. A three-level prevention and control mechanism, including “base layer acceptance, process imaging, and destructive sampling inspection,” needs to be established. Process standardization documents need to refine the threshold values for node construction errors, capture tile paving flatness deviations through AI image recognition technology, and block the transmission path of defects. The superposition of material and process risks may lead to systemic failure. It is necessary to build a cross-stage quality traceability system that correlates construction data with fault records during operation and maintenance to achieve risk traceability [5].

4.1.2. Schedule risk: Conflict in cross-construction and supply chain disruption

Conflicts in cross-construction manifest as competition among multiple professional work fronts. The mismatch in timing between the installation of electromechanical pipelines and the construction of decorative surfaces can easily lead to rework. It is necessary to optimize the logical relationship of processes based on BIM's 4D progress simulation and set up buffer zones to coordinate interface handovers. The risk of supply chain disruption is influenced by international logistics and price fluctuations of raw materials. Therefore, it is necessary to establish a main material alternative warehouse and a regional procurement network, and utilize blockchain technology to achieve real-time monitoring of supplier capacity. The transmission of progress risks exhibits nonlinear characteristics. A single node delay may trigger the reconstruction of the critical path. It is necessary to introduce Monte Carlo simulation to quantify the probability distribution of delays and develop multi-level acceleration plans [6]. Dynamic progress management requires the integration of RFID material tracking and drone inspection data to improve the response time of risk early warning by more than 40%.

4.2. Construction of risk quantification assessment model

4.2.1. Risk matrix based on fuzzy analytic hierarchy process

The Fuzzy Analytic Hierarchy Process (FAHP) utilizes triangular fuzzy numbers to handle the subjective ambiguity of expert judgments, establishing a three-tier evaluation structure of "objective layer-criteria layer-indicator layer" to quantify the weights of risk dimensions such as quality, progress, and cost. The risk matrix categorizes the probability of occurrence and the degree of impact into five levels, and combines the FAHP weights to calculate the comprehensive risk index, achieving comparable ranking of multi-source risks. The model needs to incorporate correction factors and adjust evaluation parameters based on the characteristics of engineering projects, for example, the risk weight for fire safety inspection of commercial complexes is higher than that of office buildings [7]. Empirical research indicates that the model achieves an accuracy rate of 82% in risk identification during the mechanical and electrical installation phase, surpassing traditional qualitative assessment methods.

4.2.2. Dynamic risk assessment system driven by big data

The dynamic risk assessment system relies on IoT sensors to collect real-time data on the construction environment, equipment status, and personnel behavior, establishing a risk feature library and a historical case library. Machine learning algorithms analyze the association rules between schedule delays and quality defects, and predict supply chain fluctuation trends through LSTM neural networks. The system employs a stream computing architecture to provide real-time alerts for potential hazards such as workers not wearing safety belts during high-altitude operations and material stacking overload, with response delays controlled within 3 seconds. Digital twin technology enables three-dimensional visualization and deduction of risk scenarios, assisting managers in evaluating the effectiveness of emergency plans. In super high-rise complex projects, this system has increased the identification rate of major risks by 35% and reduced the cost of risk management by 22%, verifying the engineering applicability of the technical approach.

5. Risk prevention strategies and implementation paths

5.1. Special measures for quality risk prevention and control

5.1.1. Implementation key points of the whole process model led system

The whole-process sample guidance system ensures the reproducibility of construction techniques through a dual-track verification mechanism of physical and digital samples. The sample area needs to cover typical nodes of various disciplines, and a construction error benchmark database is generated using laser scanning technology as the acceptance standard for batch construction [8]. Dynamic sample management requires the setting of reference samples every 2000 square meters of working surface during the construction process, and real-time comparison of actual engineering and sample data differences through a mobile quality inspection system. The material sealing sample library needs to integrate RFID chips to achieve automatic verification of incoming materials and sample parameters. The implementation of the system needs to be matched with a reward and punishment mechanism, incorporating the sample compliance rate into the supplier evaluation system to form a quality control closed loop of "sample development - process benchmarking - problem tracing - standard iteration".

5.1.2. Penetrative supervision mechanism of third-party testing institutions

The penetration supervision mechanism relies on independent testing institutions to implement blind sampling inspection throughout the entire process, focusing on monitoring key indicators such as adhesive strength of decorative surfaces and waterproof and closed water tests. The inspection scope extends to material production bases, and unannounced inspection mode is adopted to conduct surprise verification of the stability of suppliers' production processes. The inspection data is integrated into the blockchain platform to ensure that reports are tamper-proof and shared in real-time with all parties involved in the construction [9]. The supervision process is embedded in the process inspection node, with an intelligent contract control logic set up for "passing inspection - unlocking process". For areas with high incidence of quality issues, destructive testing combined with infrared thermal imaging is implemented for multidimensional verification. The inspection results are directly linked to the proportion of project payment, forming a rigid constraint.

5.2. Cost and schedule collaborative control strategy

5.2.1. Contract price adjustment formula and change order warning

The construction of the price adjustment formula requires the integration of price indices for bulk commodities such as steel and copper, as well as the fluctuation coefficient of labor costs. The sliding average method is employed to calculate the price difference compensation amount. The change visa early warning system analyzes drawing change records through NLP technology, automatically linking the bill of quantities with contract terms. When the cumulative change exceeds 3% of the contract price, a tiered early warning is triggered. The dynamic cost model integrates BIM quantity calculation data with supply chain price information to predict the trend of cost deviation per square meter in real-time. The visa approval process has been enhanced with a three-dimensional model comparison and verification step, which utilizes point cloud scanning to confirm the actual completion quantity of changed parts, thereby mitigating the risk of false reporting [10].

5.2.2. Critical Path Method (CPM) and resource leveling optimization

The critical path method needs to be combined with Monte Carlo simulation to quantify the uncertainty of process time and identify probabilistic critical paths. Resource leveling optimization employs genetic algorithms to solve for the optimal allocation of personnel and machinery. Through the BIM + GIS system, it simulates the thermal map of resource spatial distribution to avoid vertical transportation conflicts. Schedule control introduces the TOC theory, setting up buffer resource pools on the critical path to cope with unexpected delay events. Internet of Things devices collect data in real-time, such as tower crane utilization rates and concrete pouring efficiency, dynamically adjusting resource allocation strategies to achieve Pareto optimality in both schedule compression and cost savings.

5.3. Safety and legal risk response plan

5.3.1. AI monitoring and emergency plan drills for high altitude operations

The intelligent monitoring system for high-altitude operations integrates UWB positioning and computer vision technology to detect the wearing status of safety belts and the integrity of edge protection in real time. Violations trigger audible and visual alarms and are simultaneously recorded in personnel credit files. The emergency response plan drill utilizes digital twin technology to construct 3D scenes of accidents such as fires and collapses, and conducts multi-role collaborative disposal training through VR equipment. The drill data is integrated into the BIM operation and maintenance platform to generate a list of improvements for weak links, focusing on optimizing the escape route signage system and emergency material allocation paths. The AI system automatically analyzes historical accident cases and pushes customized safety disclosure content to the mobile terminals of operators.

5.3.2. Combined application of performance bond and engineering quality liability insurance

The performance bond adopts a demand-pay mode, with a tiered guarantee ratio mechanism, gradually releasing guarantee pressure according to the progress of the project. The engineering quality liability insurance introduces TIS institutions to conduct whole-process risk assessment, with insurance clauses embedded with key indicators such as material durability and waterproof engineering warranty period. The insurance compensation trigger mechanism is linked with third-party inspection data, and blockchain smart contracts are used to achieve automatic claims settlement. The combined application mode disperses catastrophic risks through a pooling system, establishing a three-tier risk transfer structure of "contractor guarantee-insurance company underwriting-reinsurance allocation", reducing the risk of capital chain disruption for the construction party.

6. Summary

The technical management and risk prevention of fine decoration projects require the establishment of a three-dimensional management system of "standardization-control-hedging". The technical management system forms a full-process technical closed loop through BIM collaborative design, prefabricated construction, and digital monitoring, focusing on solving the problems of multi-disciplinary interface conflicts and process standardization. The differentiated control strategy proposes modular design and flexible construction organization plans based on the functional complexity of office buildings and the dynamic demand characteristics of commercial complexes, achieving an organic balance between personalized needs and engineering efficiency. The risk prevention and control system rely on fuzzy analytic hierarchy process and big data technology to establish a quantitative evaluation model, combined with special measures such as whole-process sample guidance and penetrating inspection, effectively blocking the transmission chain of quality defects. Empirical research shows that this system has reduced the construction period by 12% and controlled the cost deviation rate within 1.5% in the application of super high-rise complexes, verifying the practical effectiveness of the management model. Future research needs to deepen the engineering integration of digital twins and metaverse technology, build an intelligent decision-making system that integrates virtual and real worlds, and promote the advancement of fine decoration projects towards a data-driven management model. The iteration of technical standards should focus on the adaptability of new environmentally friendly materials and intelligent construction equipment, forming a sustainable industry technology paradigm.

Disclosure statement

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The Practice and Innovation of Construction Control Technology of Cracks in Prestressed Members in Construction Engineering

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Abstract: This article focuses on the control of cracks in prestressed concrete structures. It explains the stress characteristics, influencing factors, and causes of crack formation during construction. The article introduces advanced technologies such as intelligent prestressed tensioning, highlights key aspects like high-performance concrete mix design, and discusses various monitoring and control methods. It also covers their practical applications and achievements in real-world projects, and looks ahead to future development directions.

Keywords: Prestress; Crack control; Concrete structure

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1. Introduction

With the development of the construction industry, prestressed concrete structures have been widely used in various engineering projects. The Guiding Opinions on Promoting the Coordinated Development of Intelligent Construction and Building Industrialization, released in 2020, emphasized the importance of intelligent and collaborative development in the construction industry. The stress characteristics of prestressed concrete structures are unique, and their pre stress is influenced by various factors. At the same time, concrete shrinkage and creep, temperature stress during construction, and tension control deviation can all lead to crack formation. Measures such as intelligent prestressing technology and optimization of high-performance concrete mix proportions are crucial for controlling cracks. These technologies are in line with policy guidance, aimed at improving building quality and durability, and promoting the intelligent and high-quality development of the construction industry.

1.1. Mechanism and technical principles of crack formation in prestressed components

1.1.1. Mechanical characteristics analysis of prestressed components

The stress characteristics of prestressed concrete structures are unique. The distribution pattern of pre stress is influenced by various factors, such as the arrangement of prestressed reinforcement and the magnitude of tension-controlled stress. Reasonable arrangement of prestressed steel bars can enable the structure to obtain compressive stress in advance before bearing loads, effectively improving the crack resistance performance of the structure. The impact of concrete shrinkage and creep on structures cannot be ignored. Shrinkage will reduce the volume of concrete and generate tensile stress, while creep will cause structural deformation to increase over time. In prestressed components, the shrinkage and creep of concrete can cause prestress loss, change the distribution of prestress stress, and affect the structural stress performance [1]. Therefore, in the design and construction process, it is necessary to fully consider these factors and take corresponding measures to control the occurrence of cracks.

1.2. Research on the mechanism of crack formation

Various factors during the construction phase can lead to the formation of cracks in prestressed components [2]. In terms of temperature stress, after pouring concrete, the hydration heat causes an increase in internal temperature, followed by shrinkage during the cooling process. When restrained, tensile stress may occur, which may lead to crack formation. When controlling the deviation of tensioning, the application of prestress is unreasonable. If the tensioning stress is too large or too small, it will change the stress state of the component. Excessive tensioning stress may cause the concrete to locally bear excessive tensile stress and crack, while insufficient tensioning stress cannot effectively offset the tensile stress generated by the load. Improper curing of concrete, such as insufficient humidity and curing time, can cause rapid loss of moisture, leading to shrinkage cracks, and also affecting the strength development of concrete, reducing its ability to resist cracks. These factors interact with each other and jointly affect the formation of cracks in prestressed components.

2. Core technology system for construction crack control

2.1. Pre stressing intelligent tensioning technology

In the domain of prestressed intelligent tensioning, the cornerstone is the creation of a BIM-based three-dimensional coordinate control system that governs every strand and tendon of prestressed reinforcement [3]. By embedding precise geometric and material attributes into a federated 3D model, BIM delivers millimeter-level spatial positioning data that guide installers in real time, eliminating the positional deviations that traditionally trigger early-age cracking and long-term durability loss. Concurrently, state-of-the-art intelligent tensioning rigs continuously synchronize hydraulic pressure, elongation, and anchor-set values across multiple jacks through high-frequency IoT sensors. Cloud analytics compare measured stress waves against BIM-derived target envelopes; any divergence exceeding tolerance thresholds triggers immediate, algorithmic compensation, dynamic pressure trimming, micro-timing shifts, or strand-specific re-tensioning, so that the final force distribution mirrors the design intent with sub-percent accuracy. The synergy of BIM spatial control and closed-loop stress governance not only upgrades the quality and uniformity of prestressed elements but also minimizes crack potential, extends service life, and underwrites structural safety in aggressive environments.

2.2. Collaborative control of concrete pouring quality

Optimizing high-performance concrete mix proportions is the linchpin of collaborative quality control during placement. Leveraging machine-learning algorithms and multi-objective genetic optimization, the system simultaneously evaluates fineness, reactivity, and particle packing of cement, aggregates, micro-silica, nano-clays, super-plasticizers, shrinkage-reducing and viscosity-modifying admixtures to predict strength, modulus, and autogenous shrinkage with laboratory-grade accuracy *in silico*. The resulting recipe is continuously refined by feeding real-time rheology and temperature data from the batch plant back into the model, ensuring crack-resistant performance under site-specific curing regimes. Concurrently, a dynamic coupling control framework integrates wireless compaction meters embedded in poker vibrators with strain-gauged formwork shores. An edge-computing module correlates vibration energy, concrete density, and formwork deflection in a closed loop, automatically modulating vibration amplitude and sequentially tightening or loosening shore screws to neutralize local stress concentrations. This real-time synchronization between mix design intelligence and placement mechanics secures uniform stress distribution, suppresses plastic settlement and thermal cracking, and delivers defect-free, durable concrete elements [4].

3. Dynamic monitoring technology for construction process

3.1. Real time monitoring system for stress field

3.1.1. Layout of fiber bragg grating sensing network

Designing the topology structure of the sensor array for prestressed critical sections is an important step in the layout of fiber Bragg grating sensing networks. The distribution position of sensors needs to be determined based on the stress characteristics of the components and key parts to accurately obtain stress information [5]. At the same time, the spacing between sensors should be considered to avoid information loss or resource waste caused by sparsity or density. Establishing a stress field data acquisition and transmission system is also crucial. The collection system needs to ensure stable and efficient acquisition of sensor data, while the transmission system needs to ensure real-time and accurate data transmission. Suitable communication protocols and transmission media can be used to timely transmit the collected data to the monitoring center for subsequent analysis and processing.

3.1.2. Multi source data fusion analysis

It is crucial to construct a numerical analysis model that couples temperature, stress, and strain multiple physical fields in order to effectively control cracks in prestressed components. Through this model, the influence of temperature changes on stress and strain can be comprehensively considered, thus more accurately simulating actual working conditions. At the same time, sensor technology is used to collect real-time multi-source data such as stress, strain, and temperature at the construction site, and these data are fused into a numerical analysis model. The process of data fusion requires the use of advanced algorithms and analysis techniques to ensure that the model can reflect the actual state of the structure in real time. On this basis, by setting reasonable thresholds and warning mechanisms, when the model calculation results show that the risk of cracks reaches a certain level, timely warning information is issued to provide a basis for construction personnel to take corresponding measures, thereby effectively preventing the occurrence and development of cracks [6].

3.2. Digital construction management platform

3.2.1. Construction of digital twin model

To establish a robust construction-process visualization system that seamlessly merges 3D laser scanning with BIM, the workflow begins by deploying high-speed, phase-based terrestrial laser scanners to capture dense, millimeter-accuracy point clouds of the evolving site. These point clouds, enriched with intensity and RGB values, are automatically registered through iterative-closest-point algorithms that leverage both target-based and targetless geo-referencing, yielding a cohesive 3D snapshot of every structural member, tendon duct, and temporary support. Next, the point cloud is aligned to the federated BIM model via a cloud-to-BIM matching engine that employs vowelized cross-correlation and semantic surface descriptors, allowing dynamic verification of as-built versus as-designed geometries.[7] Discrepancies exceeding predefined tolerances, such as misaligned anchor plates, displaced reinforcement cages, or formwork offsets and are instantly flagged in an augmented-reality dashboard, enabling crews to rectify deviations before concrete is cast or tendons are stressed. The same fusion platform continuously feeds updated geometric data to predictive crack-control modules that recalculate prestress losses and early-age restraint stresses in real time. Consequently, the integrated system not only safeguards dimensional accuracy and schedule adherence but also provides the precise, data-rich feedback loop required to prevent cracking in prestressed components throughout the entire construction cycle.

3.2.2. Design of quality traceability mechanism

In construction, establishing a construction parameter blockchain certification system is the key to quality traceability mechanism. Through this system, various parameters during the construction process, such as material properties of prestressed components, construction process parameters, etc., can be recorded and stored in real time. These data are guaranteed to be authentic and complete by the tamper proof nature of blockchain. During the construction process, data from every stage is accurately recorded, from the incoming inspection of raw materials to the processing and production of components, and then to on-site installation. This forms a traceable quality control chain throughout the entire process. Once quality problems such as cracks occur, they can be quickly traced back to the source of the problem, determining whether it is caused by material issues, construction operation issues, or other factors. Effective corrective measures can be taken to improve construction quality and management efficiency [8].

4. Technological innovation and engineering practice

4.1. Research on the application of new materials

4.1.1. Self-compacting compensating shrinkage concrete

Self-compacting compensating-shrinkage concrete (SCCSC) is a next-generation engineered material that merges two synergistic technologies: high-flowability self-compacting concrete and controlled expansive mineral systems. The mix is proportioned with optimized powder content, comprising low-heat Portland cement, finely ground slag, and limestone micro-filler, to achieve plastic viscosity below 250 Pa·s and slump-flow above 650 mm, enabling complete gravity-driven filling of congested reinforcement, thin webs, and intricate tendon profiles without any vibration [9]. Simultaneously, a precisely calibrated blend of calcium sulfa-aluminate-based Type K expansive agent, crystalline waterproofing admixture, and shrinkage-reducing polymer is incorporated to generate restrained expansion of 0.02–0.04 % within the first 7 days. This early-age expansion counteracts autogenous and drying shrinkage that typically develop later, effectively neutralizing tensile stresses that initiate micro-cracking. Real-time wireless maturity sensors embedded in the pour validate that expansion peaks before initial set, ensuring that prestressing strands remain fully bonded and that long-term prestress losses are minimized. Field trials on post-tensioned box girders show a 70 % reduction in surface crack density and a 25 % increase in chloride diffusion resistance compared with conventional vibrated concrete. By integrating SCCSC into critical prestressed elements, segmental bridges, containment vessels, and offshore platforms, where engineers secure superior durability, extended service life, and enhanced structural safety while accelerating construction schedules through elimination of vibration operations.

4.1.2. Research and development of intelligent prestressed reinforcement

The design of intelligent steel strands with built-in sensing units is the key to the development of intelligent prestressed reinforcement. This intelligent steel strand can sense its stress state in real time by cleverly integrating sensing technology. The sensing unit can accurately capture various changes in the steel strand during the stress process and convert this information into readable data. This has brought many advantages to engineering practice, such as allowing construction personnel to timely understand the stress situation of steel strands in prestressed components during the construction process, thereby more accurately controlling the construction process and avoiding problems such as cracks caused by improper stress. At the same time, real-time data feedback also helps to dynamically evaluate the safety and stability of the entire structure, providing reliable guarantees for the long-term use of buildings [10].

4.2. Innovation in construction technology

4.2.1. Pre stressing timing optimization technology

Establishing a graded tensioning timing control strategy based on the mechanical characteristics of the construction phase is the key to prestressing timing optimization technology. Through in-depth analysis of the mechanical properties of components during the construction phase, determine the appropriate timing and intensity of prestressing application at different stages. In practical operation, considering the setting and hardening process of concrete and the changes in structural stress state, accurately plan the time nodes and stress levels for graded tensioning. This strategy can effectively avoid the problem of component cracks caused by applying prestress too early or too late, and improve the quality and durability of prestressed components. At the same time, with the help of advanced monitoring technology and numerical simulation methods, real-time monitoring and feedback of mechanical parameters during the construction process are carried out to further optimize the graded tensioning timing control strategy, ensure that the construction process meets the design requirements, and achieve effective control of cracks in prestressed components.

4.2.2. Active temperature field control technology

Active temperature-field control technology has become indispensable in modern construction, especially for massive prestressed elements whose early-age thermal gradients can trigger through-section cracking and long-term durability loss. At its core lies an intelligent temperature-control and curing system that continuously monitors both the evolving hydration-heat signature of the concrete and the fluctuating ambient conditions. Embedded sensor arrays that comprising thermocouple strings, fiber-optic DTS cables, and wireless humidity probes, feed millisecond-resolution data to an edge-computing gateway. Machine-learning algorithms fuse these readings with weather forecasts and mix-specific thermal models to predict temperature trajectories up to 48 hours ahead. When the core-to-surface differential approaches a preset threshold, which typically 20 °C for high-performance mixes, and when the system autonomously triggers targeted interventions. Excessive hydration heat is dissipated via atomized misting nozzles integrated into the formwork, variable-flow embedded cooling pipes, or phase-change panels that absorb latent heat. Conversely, when ambient temperatures drop below a calibrated set-point, resistive heating blankets, infrared emitters, or circulated warm glycol loops are activated to maintain isothermal curing. The closed-loop controller continuously recalibrates valve positions, pump speeds, and heater duty cycles, ensuring that concrete remains within the optimal 10–35 °C envelope throughout the critical first 72 hours. By maintaining a dynamic equilibrium between internally generated heat and external thermal loads, the system mitigates tensile stresses in prestressed components, suppresses delayed ettringite formation, and ultimately enhances structural safety, service life, and construction quality.

4.3. Engineering application verification

4.3.1. Case study of large-span bridge engineering

Crack control technology played a key role in the construction of prestressed box girders for a certain cross sea bridge. In this project, strict control over the quality of raw materials ensured the stability of concrete performance and reduced the possibility of cracks caused by material problems. At the same time, advanced prestressing technology is adopted to precisely control the magnitude and distribution of prestressing, effectively avoiding cracks caused by uneven stress. During the construction process, real-time monitoring of temperature and humidity is carried out, and construction techniques are adjusted based on the monitoring results, such as arranging pouring time and maintenance measures reasonably to prevent cracks caused by temperature stress and shrinkage deformation. Through the comprehensive application of these crack control technologies, the crack situation of the prestressed box girder of the cross-sea bridge has been effectively controlled, improving the quality and durability of the box girder, and providing useful reference and inspiration for similar large-span bridge projects.

4.3.2. Practice of super high-rise buildings

In the practice of super high-rise buildings, the construction of the core tube prestressed transfer layer faces many challenges. Through technological innovation, the design of prestressed components has been optimized to better adapt to the complex stress conditions of super high-rise structures. During the construction process, advanced prestressing equipment and technology are used to strictly control the tensioning stress and elongation, ensuring the accuracy of prestressing application. At the same time, strengthen the quality control and mix design of concrete raw materials to improve the crack resistance of concrete. A specialized construction sequence and quality control points have been developed for the special structural form of the core tube, such as strict inspection of the steel reinforcement layout and anchoring of key parts. Through the comprehensive application of these measures, the occurrence of cracks in prestressed components has been effectively controlled, the construction quality of the core tube prestressed conversion layer has been improved, and strong guarantees have been provided for the structural safety of super high-rise buildings.

5. Summary

The construction control technology for cracks in prestressed components has achieved significant results in practice. In terms of innovation, a series of effective crack control technologies have been developed, which have significant advantages in both technology and economic benefits compared to traditional processes. Technically, it can more accurately control the occurrence of cracks; Economically, it has reduced maintenance costs caused by crack problems. At the same time, a quality management system for the entire life cycle of prestressed structures based on intelligent construction technology has been proposed, which will further enhance the ability to control cracks in prestressed components. Looking ahead to the future, digital and intelligent technologies have broad development prospects in the field of crack prevention and control. Through intelligent sensors and other devices, the status of components can be monitored in real time, and crack risks can be warned in advance. By utilizing big data analysis, crack control strategies can be continuously optimized, providing more efficient and accurate solutions for crack control of prestressed components in construction.

Disclosure statement

The author declares no conflict of interest.

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UHPC Reinforcement of Damaged RC Beams under Load Conditions Cracking and Bending Performance

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Abstract: In order to study the mechanical properties of damaged reinforced concrete (RC) beams reinforced with ultra-high-performance concrete (UHPC), a four-point bending test was conducted to systematically investigate the influence of factors such as the number of reinforcement surfaces and the degree of damage. The results indicate that single-sided repaired beams have certain advantages in crack resistance performance, but are more disadvantageous in ultimate bearing capacity, with obvious debonding phenomenon before the end of loading. Compared with single-sided reinforcement, the cracking load of the three-sided reinforced beam increased by an average of 1.85 times, the ultimate bearing capacity increased by an average of 177.5%, and a good UHPC-RC combination effect could be formed, which could work synergistically until the end of loading. The degree of pre damage has a significant impact on the crack resistance performance of reinforced beams, while its impact on the ultimate bearing capacity is relatively limited. When the pre splitting width of the RC beam increases from 0.2 mm to 0.4 mm, the ultimate bearing capacity decreases by 28.33%.

Keywords: UHPC reinforcement; Three-sided repair; Bending performance: Cracking characteristics; Ultimate bearing capacity

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1. Introduction

As the service life of reinforced concrete (RC) structures increases, the problems of damage and performance degradation become prominent, especially after repeated loading, environmental erosion, or sudden events, the components are prone to damage, affecting safety and durability. In recent years, ultra-high-performance concrete (UHPC) has great potential in the field of structural repair and reinforcement due to its excellent mechanical properties and durability. As a cement-based composite material with high density, strength, and toughness, its compressive strength usually exceeds 150 MPa. In terms of durability, the dense microstructure formed by low porosity has excellent impermeability, and the chloride ion diffusion coefficient is reduced by more than 90% compared to ordinary concrete. It can serve stably in harsh environments [1]. After high-temperature curing, the shrinkage coefficient and creep degree of UHPC are lower, and it is widely used in bridge engineering, high-rise buildings, marine structures and other fields.

In recent years, scholars have conducted extensive research on the mechanical properties of UHPC reinforced RC beams. Previous study revealed the regulatory mechanism of UHPC layer thickness on the flexural performance of RC beams through experiments and finite element simulations [2]. They found that for every 10 mm increase in thickness, the flexural stiffness can be increased by 18% to 25%. The experimental results of Yang Zhang et al. showed that the synergistic improvement of strain hardening ability of UHPC layer by reinforcement ratio and steel fiber content can significantly enhance the cracking load and ultimate bearing capacity of reinforced beams [3]. Zhang Jianrui three-point loading test showed that the thickness of UHPC reinforcement had an impact on the shear strength of RC beams, and the effect was significant when the thickness was ≥ 20 mm [4].

In terms of reinforcement methods and interface treatment, Zhu Jingwei conducted bending tests and finite element analysis on steel UHPC-NC composite beams, which showed that the UHPC layer can significantly improve the flexural bearing capacity [5]. The interface chiseling and shear reinforcement can achieve complete combination (without slip), and the plastic failure characteristics are obvious. Al Osta used two different reinforcement techniques (sandblasting on the surface of RC beams and bonding with epoxy adhesive), and the results showed that both techniques had good bonding strength at the interface, ensuring the integrity of the composite structure [6]. Meanwhile, some scholars are also concerned about the improvement of fatigue performance and durability. Tohru verified the effectiveness of UHPC layer in controlling the damage of RC components through bending fatigue tests, and proposed a numerical model considering the pre damage of RC beams, the fracture characteristics of RC and UHPC, and the elastic-plastic behavior of steel bars for fatigue life prediction [7]. Research has shown that UHPC reinforcement of damaged RC structures can effectively improve crack resistance and durability, and extend their service life.

Based on this, this article focuses on the reinforcement of damaged RC beams with UHPC. Through four point bending tests, the influence of the number of reinforcement surfaces and the degree of damage on RC beams was explored, and the role of both in resisting bending capacity was further analyzed. This study aimed to provide theoretical support and technical reference for the efficient repair and performance prediction of damaged RC structures in engineering.

2. Material and methods

2.1. Overview of the experiment

A total of four reinforced concrete (RC) beams were fabricated in this experiment. One of them served as the control beam without any damage or strengthening treatment (denoted as BC-0). The remaining three beams were repaired and strengthened using ultra-high-performance concrete (UHPC) with variables including the number of strengthened surfaces and the degree of damage. Details of the specimens are shown in **Figure 1**. The RC part of each test beam has a height of 400 mm, a width of 200 mm, and a length of 2600 mm, with a calculated span of 2400 mm. A four-point loading scheme was adopted for the test beams, resulting in a pure bending segment of 640 mm. For longitudinal reinforcement (LR), 3 bars of Φ18 mm were arranged on the tensile side of the cross-section, and 2 bars of Φ10 mm on the compressive side. As for stirrups (HR), Φ10 mm bars were placed at a spacing of 80 mm in the bending-shear segments and 160 mm in the pure bending segments. Except for the control beam, the other test beams were repaired and strengthened with a 50 mm thick UHPC layer, which contained a layer of Φ3

× Φ3 steel mesh (MR) with a mesh size of 30 mm × 30 mm. Detailed information of the test beams is provided in **Table 1**. The letters in the table have the same meanings as defined above. For example, B1-0.2 refers to the test beam that was pre-cracked to a maximum crack width of 0.2 mm at the bottom and then repaired on the single bottom surface; while B3-0.2 represents the test beam that was pre-cracked to 0.2 mm at the bottom and then repaired on three surfaces (the bottom and two sides).

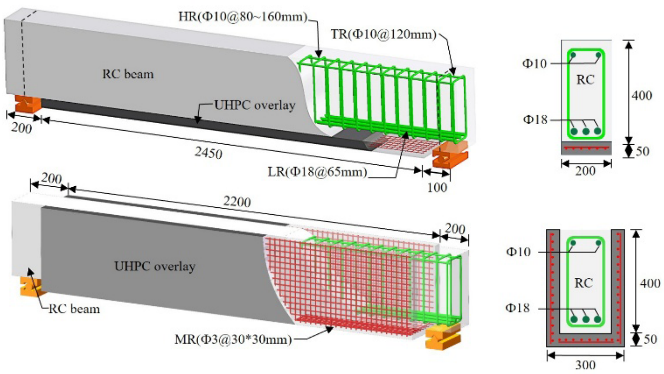

Figure 1. Detailed Scheme of Test Piece.

Table 1. Detailed information of test beams

Serial Number	Member Number	Repaired Surface	Pre-damage
1	BC-0	-	-
3	B1-0.2	1	0.2 mm
5	B3-0.2	3	0.2 mm
7	B3-0.4	3	0.4 mm

1.2. Test piece material

In the experiment, the normal concrete (NC) was designed as C50 strength grade concrete, composed of cement, sand, gravel, water, and water reducer, with its mix proportion given in **Table 2**. The ultra-high-performance concrete (UHPC) used was a commercial dry-mix product of Xingguli U120-2% type, whose main components include cement, silica fume, fly ash, quartz powder, quartz sand, high-performance plasticizer, and steel fibers. Among them, the steel fibers are straight ones with a diameter of 0.2 mm and a length of 13 mm, with a volume content of 2%. Their tensile strength is higher than 2000 MPa, and elastic modulus is 200 GPa. Basic mechanical parameters of NC and UHPC were obtained through material performance tests on concrete mechanics, as shown in **Table 3**. The test beams adopted HRB400 reinforcement, where the yield strength of Φ10 mm steel bars is 472.5 MPa, and that of Φ18 mm steel bars is 465 MPa.

Table 2. Mix Proportion of NC (Unit: kg/m^3)

Component	Cement	Crushed Stone	Sand	Water	High-Efficiency Water Reducer	Water-Cement Ratio
Mass (kg/m³)	470	1048	771	122	4	0.26

Table 3. Mechanical Properties of Concrete Materials

Type of Concrete	Curing Condition	Compressive Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)
C50	Natural Curing	46.5	8.9	38.6
UHPC	Natural Curing	144.3	25.6	47.1

1.3. Sample production process

The fabrication process of pre-damaged RC beams strengthened with UHPC layers is illustrated in Figure 2, which mainly includes the following steps: (a) Casting of RC beams: After casting, the RC beams were cured at room temperature for 28 days, followed by further curing at room temperature for more than 90 days. (b) Pre-damage introduction: The RC beams were first pre-loaded and then strengthened. The degree of pre-damage was evaluated by the maximum crack widths introduced in the RC beams under pre-loading, which were set to 0.2 mm and 0.4 mm respectively. (c) Interface treatment before strengthening: After the pre-damage degree was reached, the test beams were unloaded, and the surfaces of the RC beams to be strengthened were chiseled. (d) Casting of UHPC layers: For the beams with completed interface treatment, the steel meshes were positioned, and UHPC was used for repair. The formwork was removed after standard curing for 28 days. (e) Destructive testing: After the repair of the test beams was completed, a four-point bending loading test was carried out from the initial state until failure.

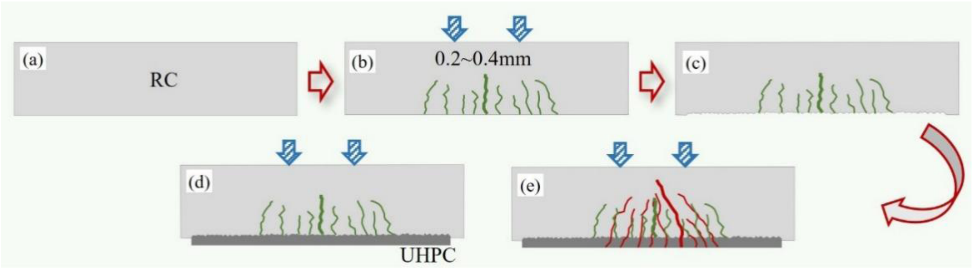

Figure 2. Preparation of experimental beam.

1.4. Test setup and instruments

In the pre-cracking stage, all test beams except the control beam were loaded according to the pre-damage conditions specified in **Table 1**. The initial load increment was set to 5 kN per step to compact the beam body, preventing damage to the loading device and the beam due to excessive load increments, which could affect the test accuracy. Subsequently, pre-damage loading was conducted with a load increment of 10 kN per step, and a crack observer was used to continuously monitor the development of major cracks. When approaching the pre-damage value, the load increment was adjusted to 5 kN per step to obtain the accurate load corresponding to the target damage value. Loading was stopped once the beam reached the pre-damage value, and relevant data were recorded before unloading at an increment of 2 kN per step. During formal loading, the initial load increment was 10 kN per step, which was reduced to 5 kN per step when approaching the cracking load. After the RC beam cracked, the load increment was restored to 10 kN per step. When the load reached 80% of the theoretical peak value, displacement-controlled loading was adopted at a rate of 1 mm/min, with a mid-span deflection increment of 1 mm per step. After maintaining the load, cracks were observed until the specimen lost its load-bearing capacity. In terms of measuring points: Dial gauges were installed at the top of the beam-end supports, mid-span, and the supports of the distribution beam to measure settlement and deflection; Dial gauges were mounted at the interface between the UHPC and RC layers to measure slip and debonding; Strain gauges were attached to the side surfaces of the test beam and the surface of tensile reinforcement to measure strain; An extensometer was installed at the bottom of the beam to record the tensile deformation of the UHPC layer after cracking. The arrangement of measuring points and strain gauges for single-sided and three-sided repaired beams was similar as shown in **Figure 3**.

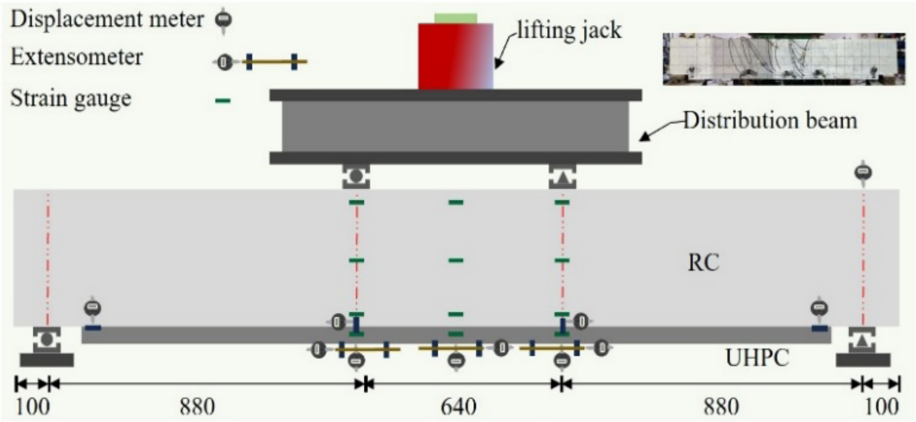

Figure 3. Test set up and lay out of measuring points.

2. Failure modes and crack distributions

The failure modes and crack development patterns of the test beams are shown in **Figure 4**. For the single-sided repaired beam, when loaded to 0.7 Pu (Pu is the ultimate load of the test beam), debonding occurred at the UHPC-NC interface, causing the UHPC to gradually disengage from load-bearing, and the RC beam had to bear the load alone, leading to crushing of the NC at the top. Compared with the control beam BC-0, the crack resistance of the single-sided strengthened test beam was significantly improved, with the cracking load reaching 1.85 times that of the control beam (**Table 4**), while the flexural load-bearing capacity was comparable to that of the undamaged control beam. The three-sided repaired beam exhibited good cooperative force-bearing and overall performance throughout the loading process. Compared with the control beam, the cracking load increased by 1.69–2 times, and the flexural load-bearing capacity increased by 1.63–1.92 times. As shown in **Figure 4**, there were significant differences in crack development and distribution among the test beams. The control beam BC-0, an unrepaired RC beam, showed typical characteristics of flexural failure in RC beams: cracks in the pure bending segment developed vertically upward, slightly inclined near the supports, and the cracks were sparsely and uniformly distributed overall. At failure, most cracks penetrated the beam height with widths exceeding 0.2 mm, and crushing occurred in the upper part of the beam. For the single-sided repaired beam B1-0.2, obvious debonding at the UHPC-NC interface was observed. The crack distribution on the RC surface was similar to that of the control beam. Due to the disengagement of UHPC from load-bearing in the later loading stage, crushing also occurred in the upper part of the RC.

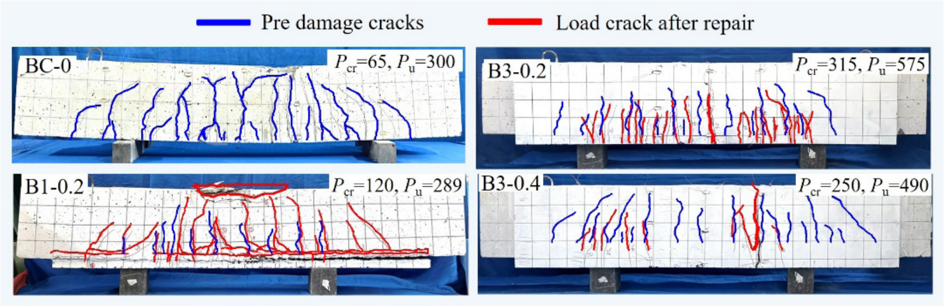

Figure 4. Experimental beam failure mode and crack distribution.

3. Load-deflection response

The load-midspan deflection curves of the test beams are shown in **Figure 5**, and their load-displacement responses can be divided into four stages: (i) Elastic stage (0–0.54 Pu for three-sided repaired beams, 0–0.43 Pu for single-sided repaired beams): The stiffness of the beams was close to that of the control beam, and the UHPC remained uncracked, resulting in linear curves. The slope of the curve for the single-sided repaired beam was very close to that of the control beam; the elastic stage of the three-sided repaired beam was significantly longer, with a notably improved stiffness. (ii) Working stage with cracks (0.54–0.93 Pu for three-sided repaired beams, 0.43–0.76 Pu for single-sided repaired beams): For the three-sided repaired beam, the UHPC layer cracked first, accompanied by multiple fine and dense cracks. The stiffness degradation was not obvious; although the slope of the curve was lower than that in the elastic stage, it still increased approximately linearly within a relatively large load range, performing better than the control beam. In this stage, the repaired layer of the single-sided repaired beam deboned, and the curve slope was close to that of the control beam, with its stiffness significantly lower than that of the three-sided repaired beam. This indicates that mere chiseling treatment is insufficient to achieve collaborative work at the interface. (iii) Yield stage (0.93 Pu–Pu for three-sided repaired beams, 0.76 Pu–Pu for single-sided repaired beams): The steel bars in the beam gradually yielded, and the deflection and crack width developed rapidly. The curve of the three-sided repaired beam dropped sharply, with a significant decrease in stiffness; for the single-sided repaired beam, as the load increased, the UHPC layer deboned and eventually ceased to work, leading to intensified deformation and an approximately straight curve. (iv) Failure stage (≥ Pu): The load dropped suddenly, the deflection increased sharply, and the cracks expanded significantly. The curve of the three-sided repaired beam entered the descending segment, with the slope tending to flatten in the later stage, and it still maintained good flexural capacity after failure; due to the debonding of the UHPC layer, the failure process and curve change of the single-sided repaired beam were close to those of the control beam, similar to conventional RC beams.

In summary, the stiffness advantage of the three-sided repaired beams stems from the composite effect between UHPC and the RC beam, as well as the synergistic constraint of multiple interfaces.

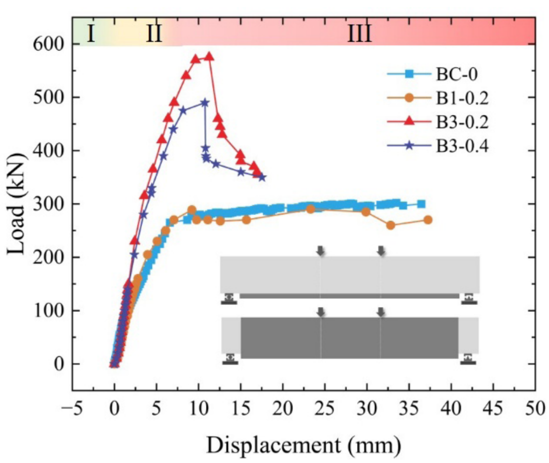

Figure 5. Load-Midspan deflection curves.

4. Conclusions

In this paper, a study on pre-damaged RC beams strengthened with UHPC was conducted. Through four-point bending tests, the effects of factors such as the number of strengthened surfaces and different damage degrees on the RC beams were investigated, and the following conclusions were drawn:

(1) In terms of the number of strengthened surfaces, compared with single-sided strengthened beams, the three-sided strengthened beams showed an average increase of 1.13 times in cracking load and an average increase of 183.92% in ultimate bearing capacity. Moreover, they could form a good UHPC-RC composite effect, maintaining collaborative work until the end of loading.

(2) The degree of pre-damage had a significant impact on the crack resistance of the strengthened beams, but a relatively limited effect on the ultimate bearing capacity. When the pre-crack width of the RC beams increased from 0.2 mm to 0.4 mm, the cracking load decreased by 13.79%-34.92%, and the ultimate bearing capacity decreased by 6.09%. The above rules were more obvious for the beams repaired after unloading.

Disclosure statement

The authors declare no conflict of interest.

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Design Strategies for Complex Mountain Highway Bridge

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Abstract: This article discusses the design strategy of complex mountain highway bridges. During the research phase, details were obtained based on prior literature review and analysis of engineering materials from mountainous area bridges. After analyzing the design characteristics of complex mountainous area road and bridge projects, the principles for the design of bridges on complex mountainous area expressways were proposed. The research on bridge design was carried out from five dimensions: bridge type selection, foundation design, superstructure design, connection part design, and material and technological innovation. Eventually, a relatively complete design system was formed. It is expected that this paper can provide technical references and value for road and bridge projects in China and promote the sustainable development of China's road traffic system from a macro perspective.

Keywords: Complex mountainous area; Bridge design; Bridge type selection; Superstructure

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1. Introduction

Driven by the development of economic construction, the scale of China's transportation routes continues to expand, effectively realizing the resource interoperability of urban and rural areas, and the mileage of highways constructed in complex mountainous areas is also expanding [1]. However, during the design of highway bridges in complex mountainous areas, design units often need to face the challenges of complex terrain, geological conditions and ecological protection. Therefore, exploring the design strategy of highway bridges in complex mountainous areas is a high-value study to further improve the design level of highway bridges, meet the demand for resource exchange between mountainous areas and towns, and ensure the durability of bridges [2].

2. Design characteristics of road and bridge engineering in complex mountainous areas

Due to a series of special factors such as geological conditions, topography, landforms and climate environment, the road and bridge projects in complex mountainous areas have three distinct features during the design period: emphasizing terrain adaptability, geological complexity and ecological protection design.

2.1. Emphasize terrain adaptability

The terrain in complex mountainous areas is highly undulating and has significant elevation differences. In the design of road and bridge projects, great importance must be attached to the adaptability to the terrain. During the route planning stage, it is necessary to fully consider the trend of the mountains, the distribution of the valleys and the course of the rivers. Meanwhile, to effectively overcome terrain obstacles, reasonable measures such as line extension design should be adopted. By extending the line length and other forms, the slope of the longitudinal slope can be effectively reduced to ensure the safe passage of pedestrians and vehicles.

2.2. Emphasize geological complexity

Complex mountainous areas are characterized by variable and complex geological conditions, which pose huge challenges to the design of road and bridge projects. For example, the geological features of caves and dark rivers under the karst geomorphology area may lead to the instability of bridge foundations, roadbed collapse or even cause landslides and mudslides. Therefore, detailed ground investigation and risk assessment should be carried out during the design period, and reasonable reinforcement and support measures should be selected based on the ground investigation materials and risk assessment results to improve the stability [3].

3. Design principles for expressway bridges in complex mountainous areas

3.1. Safety

When conducting the design stage of expressway bridges in complex mountainous areas, safety is the primary consideration. The mountainous terrain is complex and geologically variable, and natural disasters such as earthquakes, mudslides and landslides may exist in some areas. The complex mountainous environment requires that the structural design of expressway bridges must have sufficient strength, rigidity and stability. Based on detailed geological exploration materials, the underlying structure and geotechnical mechanics parameters should be mastered.

3.2. Balancing economy and environmental protection

In the design of highway bridges in complex mountainous areas, while ensuring design quality, economic and environmental considerations must also be taken into account. Efforts should be made to optimize the design plan and reduce construction costs by rationally selecting building materials and construction techniques.

Meanwhile, during the bridge design phase, the requirements for environmental protection in mountainous areas should be fully considered. The impact of site selection and design on natural vegetation and wildlife habitats should be minimized as much as possible. Moreover, construction techniques such as retaining walls should be reasonably utilized to prevent soil erosion, achieving a balance between engineering economic benefits and environmental protection benefits [4].

3.3. Adequate consideration of accessibility for post-maintenance and reinforcement

The environment where complex mountainous highway bridges are located is extremely harsh, and the accessibility of subsequent maintenance and reinforcement work is of vital importance. Therefore, during the design of the bridge, sufficient space should be reserved for later maintenance and reinforcement to ensure that the maintenance and inspection teams can easily reach the key maintenance areas such as the bridge piers, beams, and fabrication processes of the bridge during the later maintenance and repair stages [5].

4. Research on design strategies of expressway bridges in complex mountainous areas

The design of highway bridges in complex mountainous areas focuses on the selection of bridge types, foundation design, upper structure design, connection part design, as well as the innovation of similar materials and technologies to enhance economic benefits and construction quality.

4.1. Bridge type selection

When conducting highway bridge design in complex mountainous areas, the selection of bridge type is of vital importance. To meet the requirements of safety, economy and environmental protection, multiple factors such as topography, geology, hydrology and climate need to be comprehensively considered, and specific forms such as beam bridges and cable-stayed bridges should be reasonably chosen. **Table 1** presents the characteristics and applicable environmental parameters of different bridge types.

Table 1. Characteristics of Different Bridge Types and Applicable Environmental Parameters

Bridge type	Characteristics	Applied environment
Rigid bridge	It has a simple structure, mature construction technology and low cost. It has stable mechanical properties and mainly bears the bending moment caused by vertical loads. The spanning capacity is limited, and it is generally more suitable for small and medium spans.	It is suitable for mountainous sections with relatively flat terrain and good geological condition.
Suspension bridge	It has strong spanning capacity, elegant structural shape and reasonable force-bearing system. The stay cables transfer the load of the main beam to the tower, reducing the burden on the main beam and enhancing the stiffness of the bridge. There are various construction methods, and techniques such as cantilever pouring and cantilever assembly can be selected according to the actual situation.	It is often used in complex mountainous areas spanning large valleys and rivers.
Arch bridge	It has an attractive design and can fully utilize the compressive strength of the masonry materials, thus having a relatively large spanning capacity. Arch Bridges have high requirements for foundations and complex construction techniques.	It is suitable for construction in canyon areas with solid rock foundations in mountainous regions.
Suspension bridge	It has an extremely strong spanning capacity, relies on suspension cables to bear loads, and has unique force characteristics. Suspension Bridges have relatively low stiffness and are prone to vibration under wind loads, thus having high requirements for the wind environment.	It is suitable for mountainous canyons that require extremely large spans.

During the selection of bridge types, the actual conditions of mountainous areas should be fully considered. Seismic performance of bridges should be prioritized in earthquake-prone mountainous areas. In areas with strong winds, special attention should be paid to the wind resistance stability of the bridge structure. In addition, the selection phase needs to weigh the pros and cons in relation to construction conditions and maintenance costs.

4.2. Basic design

During the foundation design period, the geological conditions of the complex mountainous area are extremely complicated, and the geological investigation work needs to be carried out strictly before the design, so as to obtain comprehensive information on the stratum structure, geotechnical parameters, and groundwater level, and provide a solid basis for the foundation design.

4.2.1. Rock foundation

For rocky foundations in mountainous areas, if the investigation results show that the rocks have high strength and good integrity, it is advisable to reasonably expand the foundation to directly transfer the bridge load to the foundation rocks. This form of foundation is easy to construct and less expensive. For example, for hard granite foundations in mountainous areas, open excavation can be used to expand the foundation form, combined with the scientific design of the foundation size and depth to ensure that the foundation is in a highly stable state for a long time [6].

4.2.2. Soft soil foundation

For soft land foundation in mountainous areas, the use of pile foundation is recommended. Pile foundation can transfer the load to the deep stable soil layer and rock, and improve the bearing capacity and stability of the foundation. Under the background of different geological conditions and engineering demands, the injection pile and prefabricated pile can be reasonably selected according to the demand. Among them, the grouted pile technology allows flexible adjustment of the pile diameter and length according to the actual situation on site during the later construction period. Prefabricated piles can improve the construction speed and have the advantage of easy quality control.

4.2.3. Karst areas

For karst areas in mountainous regions, detailed investigation of the distribution of cavities and erosion fissures should be carried out before foundation design, followed by the rational use of treatment measures for traversing cavities, avoiding cavities and filling cavities. For example, long piles can be used to penetrate through the cave, with the pile ends resting on stable bedrock. For smaller caves, the form of grouting and filling can be used to improve foundation stability [7].

4.3. Superstructure design

During the design stage of the upper structure of a complex mountainous highway bridge, designers need to comprehensively consider the span of the bridge, load level, site topography conditions, and the difficulty of subsequent construction, in order to ensure that the structure has good applicability, economy, and safety.

4.3.1. Superstructure design of small and medium-span bridges

For the design of the upper structure of medium and small-span bridges, a prestressed concrete beam bridge form can be adopted. The prestressing technology not only enhances the crack resistance and load-bearing capacity of the beams, but also effectively reduces the cross-sectional size and weight of the beams. For example, “pre-tensioning” or “post-tensioning” can be adopted to produce prestressed concrete hollow core slab girders or T-beams, which are prefabricated in factories and then transported to the site, where construction teams are organized to carry out installation. This structural form not only has mature construction techniques but also enables large-scale production of prefabricated components, effectively reducing construction costs. During the design process, it is necessary to rationally arrange the prestressed tendons and optimize the mechanical performance of the components through precise mechanical calculations.

4.3.2. Design of the upper structure of long-span bridges

For long-span bridges, steel-concrete composite beam bridges can be adopted [8]. The steel-concrete composite beam form combines the tensile strength of steel and the compressive strength of concrete. It features light weight, large spanning capacity, and fast construction speed in the later stage. In complex mountainous areas, steel-concrete composite beam bridges can reduce the number of bridge piers and lower the difficulty of foundation construction. For example, in the design of bridges spanning deep valleys, a combination of steel beams and concrete bridge decks is used. Through shear connectors, the two components can work together to bear the loads from both themselves and vehicle traffic. During the design process, it is necessary to accurately calculate the shear force transfer between the steel beams and the concrete bridge deck, ensuring that the overall performance of the combined structure meets the design requirements. At the same time, the possible impacts of the shrinkage and creep characteristics of different materials on the upper structure should be fully considered.

4.3.3. Consideration of influencing factors

During the design of the superstructure of bridges in mountainous areas, designers need to take into account the impacts brought by various special loads such as temperature changes, seismic actions, and wind loads. On this basis, expansion joints and supports should be reasonably set for the superstructure to ensure that the superstructure can freely adapt to the deformation caused by temperature changes. Meanwhile, designers can conduct wind tunnel tests to conduct in-depth analysis of the impact of wind loads on the bridge structure. Based on the test results, they can optimize the cross-sectional form of the bridge or implement measures such as setting up wind barriers.

In addition, for earthquake-prone areas, seismic isolation and damping techniques should be reasonably added during the design period, such as setting lead-core rubber bearings and dampers for the superstructure to improve the seismic performance of bridges.

4.4. Design of connection parts

As a key node of a bridge, the design quality of the connection part directly affects the overall performance, safety and stability of the bridge. Connection parts usually cover the connections between beams, between beams and piers, and between piers and foundations. The connection methods and technical key points for different parts can be referred to **Table 2**

Table 2. Key points for design of bridge connection parts in complex mountainous areas

Connection points	Technical points
Between beams	Install the prefabricated beams, pour concrete into the reserved grooves of adjacent beams, and make the beams form a whole.
Between beams	Prestressed tendons connect components and beams
Between beam and pier	Select suitable bearings, such as the height of higher piers, the use of vibration isolation bearings (lead rubber, high damping rubber)
Between pier and foundation	Pour the bridge piers and foundations as a whole into one structure
Between pier and foundation	Consider pile arrangement, pile top reaction force and abutment load in the design stage of bearing platform, and reasonably design the size and reinforcement of bearing platform

As shown in **Table 2**, during the wet joint connection stage between beams, considering the inconvenience of transportation, it can be appropriately and reasonably adjusted to a dry joint form. However, the dry joint connection has extremely high precision requirements. During the construction design period, it is necessary to require the construction unit to adopt advanced measuring equipment and provide technical guarantee measures. For the connection between the beam and the pier, the selection of the appropriate bearing is of vital importance. During the design stage, the type of bearing should be reasonably selected based on the specific conditions of the bridge.

At the same time, regular inspection and maintenance are necessary to ensure that the performance of the bearing is good. The connection between the bridge piers and the foundation, whether it is achieved through overall pouring or via the use of a transfer slab, must undergo a thorough technical briefing. This ensures that the construction unit operates strictly according to the drawings, thereby guaranteeing the strength and stability of the connection area.

4.5. Innovation in materials and technologies

In the design of complex mountainous highway bridges, material and technological innovations aim to enhance the performance of the bridges, reduce engineering costs, and ensure that the bridges are better adapted to the complex environment.

4.5.1. Material innovation

In terms of material innovation, at present, the application of high-performance concrete in road and bridge engineering is becoming increasingly widespread. High-performance concrete not only possesses technical advantages such as high strength, excellent working performance and good durability, but also can significantly enhance the service life and load-bearing capacity of bridge structures. In complex mountainous areas, bridges are constantly exposed to harsh conditions over a long period of time, and they have higher requirements for the durability of concrete compared to urban bridges [9]. Therefore, during the design stage, the impermeability, erosion resistance, frost resistance and other properties of concrete can be improved by optimizing the concrete mix ratio and rationally designing the addition schemes of mineral admixtures and additives. For example, in the design of bridges near mountainous rivers, sulfate-resistant high-performance concrete can be used to resist long-term erosion by river water and extend service life.

4.5.2. Technological innovation

In the field of technological innovation, at present, bridge health monitoring technology has been widely applied in the safe operation of bridges both at home and abroad. During the design of complex mountainous highway bridges, this technical system can also be applied to enhance the management level of the bridges during their subsequent operation. During the specific implementation phase, sensors can be installed within the bridge structure to monitor the stress, strain, vibration, displacement and parameters of the bridge during operation.

At the same time, by leveraging the big data and artificial intelligence technologies of the central control platform, the monitoring data can be analyzed and processed to ensure that the operation unit can promptly identify potential diseases and safety hazards of the bridge structure. For example, fiber-optic sensors can be used to monitor the stress changes in bridges, and after the sensors complete data collection, the data can be transmitted remotely and shared in real time based on Internet of Things technology.

In addition, industrialized construction technology has already demonstrated broad prospects in bridge construction projects. During the bridge design using prefabricated assembly technology, 3D printing and intelligent construction technology can be integrated to further improve the efficiency and accuracy of bridge construction in complex mountainous areas, promote the construction of highway bridges in complex mountainous areas to break through to the field of "intelligent construction", and reduce the damage to the ecological environment of mountainous areas caused by the traditional construction forms while improving the economic benefits [10].

5. Conclusion

This research focuses on the design of highways' bridges in complex mountainous areas, deeply analyzing the design characteristics and principles of highway and bridge projects in such areas. At the same time, it proposes design strategies for the selection of highways' bridges in complex mountainous regions, ensuring that the design level of highways' bridges in complex mountainous areas can be comprehensively improved by making reasonable choices of bridge types, optimizing the design of foundations, optimizing the design of upper structures and connection parts, and applying new materials and new technologies.

In the future, for the design of complex mountainous highway bridges, further research can be conducted focusing on the design of highway bridges in complex mountainous areas. In-depth analysis of the design characteristics and principles of highway and bridge projects in complex mountainous regions should be carried out. At the same time, design strategies for the selection of highway bridges in complex mountainous areas should be proposed. To ensure this, the design level of complex mountainous highway bridges can be comprehensively improved through the reasonable selection of bridge types, the optimization design of foundations, the optimization design of the superstructure and connection parts, as well as the application of new materials and new technologies.

In the future, for the design of highway bridges in complex mountainous areas, we can try to further study the design of highway bridges focusing on complex mountainous areas, deeply analyze the design characteristics and principles of road and bridge projects in complex mountainous areas, and at the same time, put forward the design strategy of highway bridges in complex mountainous areas, to ensure that the design level of complex mountainous expressway bridges can be comprehensively enhanced through the reasonable selection of bridge types, the optimized design of foundations, the optimized design of superstructures and connection parts, as well as the application of new materials and new technologies.

We can further integrate emerging technologies, such as smart materials and new construction techniques, to effectively explore new ideas for further enhancing the performance and safety of bridges, and to better achieve ecological protection, thereby promoting the construction of mountainous area transportation facilities to a new level.

Disclosure statement

The author declares no conflict of interest.

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Research on the Integration of Public Building Design and Elderly-Friendly Living Spaces

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Abstract: This paper explores how the physiological characteristics and behavioral patterns of the elderly influence the design of elderly-friendly living spaces. It introduces key design principles and technical applications including barrier-free design and energy-saving materials. The discussion includes elderly-friendly evaluation models, research on intergenerational integration communities and other relevant topics. This paper emphasizes the need to improve design standards, promote policy innovation and establish a comprehensive theoretical framework to support the development of inclusive and sustainable environments for aging populations.

Keywords: Optimal aging residential space; Public building design; Aging population

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1. The coupling relations between the basic theories of public building design and the demand for elderly-friendly design

1.1. Theoretical framework for the design of age-friendly living spaces

The elderly group has unique physiological characteristics and behavioral patterns, which are important bases for the design of elderly-friendly living spaces. From the perspective of physiological characteristics, the physical functions of the elderly decline, such as reduced vision and hearing, and difficulty in movement. This requires that spatial design fully consider their body scale and activity ability, and rationally plan the spatial dimensions and layout based on ergonomics.

In terms of behavioral patterns, the social, leisure and daily activities of the elderly have specific rules and demands, and the functional zoning of public spaces should be adapted to them. For example, set up quiet rest areas, social areas for convenient communication, etc. The principle of barrier-free design is of vital importance in architectural planning. It is necessary to ensure that the passageways are wide and unobstructed, the ground is anti-slip, and handrails are installed, etc., to guarantee the safety and convenience of the elderly [1].

1.2. Green building design standards and low-carbon goals

The BREEAM/LEED certification system provides an important energy management indicator framework for public building design. These indicators are particularly crucial in elderly-friendly public buildings. For instance, the energy consumption of buildings must comply with specific standards to ensure that while meeting the usage needs of the elderly, efficient energy utilization is achieved [2]. This involves the insulation and heat insulation performance of buildings, as well as the optimized design of lighting, ventilation and other systems.

New low-carbon building materials play a positive role in regulating the physical environment of elderly living spaces. They can effectively improve the thermal comfort indoors and reduce energy consumption. Meanwhile, the use of low-carbon building materials also complies with green building design standards and low-carbon goals, providing the elderly with a healthier, more comfortable and sustainable living environment.

2. Innovative paths for architectural planning in the context of urban renewal

2.1. Strategies for adapting existing space to the needs of the elderly

The adaptation of existing space for the elderly needs to rely on scientific assessment and innovative strategies. The elderly-friendly evaluation model based on Geographic Information System (GIS) quantitatively analyzes the impact of the built environment on the lives of the elderly by integrating data such as terrain, transportation, and surrounding facilities, providing data support for renovation [3]. For existing buildings, optimizing vertical transportation is crucial. It is necessary to add barrier-free elevators to ensure their smooth operation and speed that meets the needs of the elderly.

At the same time, the elevator positions should be reasonably arranged to shorten the walking distance and enhance the convenience of use. Functional integration and renewal are another important path. It breaks through the limitations of traditional single functional zones and creates multi-dimensional living spaces by integrating medical, leisure, social and other functions. The renovation plan should focus on the flexibility and inclusiveness of the space, such as setting up multi-functional areas that can accommodate both daily care and social activities, to meet the diverse physical and psychological needs of the elderly.

This strategy significantly enhances the elderly-friendly nature of existing spaces through precise assessment and functional optimization, creating a safe, convenient and comfortable living environment for the elderly and promoting the deep integration of public buildings and elderly-friendly living spaces in urban renewal.

2.2. Research on the spatial layout of intergenerational integration communities

Under the background of urban renewal, the research on the spatial layout of intergenerational integrated communities focuses on the coordination and spatial optimization of the activity characteristics of different age groups.

Based on the theory of spatial syntax, by analyzing the activity trajectories of the elderly and the young within the community, the differences in their spatial usage habits and demands are revealed. The elderly tend to engage in low-intensity social and recreational activities, preferring quiet and accessible spaces, while young people pay more attention to dynamic leisure and social interaction, and require flexible and versatile functional areas [4]. Based on this, an inclusive shared space system is designed, such as multi-functional leisure squares and green rest areas, to promote intergenerational communication and interaction. Integrate flexible functional modules into the planning to endow the space with dynamic adaptability. For instance, community activity centers can achieve spatial zoning through movable partitions or multi-functional furniture, and be adjusted according to different time periods to become reading rooms for the elderly or fitness areas for the youth. The research also emphasizes the optimization of spatial scale for the elderly, ensuring barrier-free passage and safety, while taking into account the activity needs of the younger generation.

This layout strategy, through data-driven and functionally integrated design, provides efficient and inclusive spatial solutions for intergenerational integrated communities, contributing to the sustainable development of urban renewal and social harmony.

3. Intelligent construction technology innovation application system

3.1. Application of digital twin technology in aging-friendly design

3.1.1. Construction of BIM-MEP collaborative design platform

The BIM-MEP collaborative design platform plays a key role by integrating data from multiple disciplines such as architecture, structure, water supply and drainage, electrical engineering, and HVAC, achieving efficient information sharing and cross-disciplinary collaboration. The platform supports the development of an integrated pipeline system for aging-friendly equipment, optimizing the spatial environment based on the physiological needs of the elderly [5].

By using dynamic simulation technology, the impact of physical parameters such as thermal environment and light environment on the living experience can be precisely analyzed, helping designers evaluate the applicability of different schemes. Thermal environment simulation can optimize the layout of heating and ventilation systems, ensure stable indoor temperature, and meet the comfort needs of the elderly.

Light environment simulation guides the rational configuration of window positions and lighting devices, reduces the risk of glare, and improves visual comfort. The application of this technology significantly enhances the decision-making accuracy in the design stage and ensures the alignment of spatial functions with the physiological characteristics of the elderly. The platform also supports real-time data feedback and iterative optimization, promoting the refined adjustment of design schemes, providing a scientific basis for building a safe and comfortable elderly-friendly living environment, promoting the innovative practice of intelligent construction technology in the integration of public buildings and elderly-friendly spaces, and creating high-quality living spaces for the elderly.

3.1.2. VR scene simulation and user experience optimization

Through VR technology, a virtual testing environment driven by the behavioral data of the elderly can be established, providing precise basis for elderly-friendly design. By leveraging digital twin technology, real public buildings and living spaces are digitally modeled to simulate the behavioral patterns and activity trajectories of the elderly in a virtual environment. By collecting and analyzing the behavioral data of the elderly in VR scenarios, such as walking speed, dwell time, and operation habits, we can understand their demands and feedback on spatial scale and identification systems. This helps to improve the design of spatial scale, ensuring that the width of passageways, room sizes, etc. are in line with the physical characteristics and mobility of the elderly.

At the same time, it can also optimize the design of the signage system to make it clearer and more understandable, facilitating the identification and use by the elderly, improving their quality of life and independence, and providing scientific and effective methods and references for the design of elderly-friendly living spaces [6].

3.2. Development of AI-assisted decision-making systems

3.2.1. The application of machine learning algorithms in spatial demand forecasting

With the intensification of population aging, the integration of public building design and elderly-friendly living spaces have become an important research direction. In this process, machine learning algorithms can be utilized for space demand prediction. By collecting a large amount of physiological index data of the elderly and applying advanced machine learning algorithms for analysis and processing, an intelligent plane layout generation algorithm is trained. This algorithm can rationally optimize the proportion of functional rooms based on the physical condition and living habits of the elderly. For instance, considering that the elderly have difficulty moving around, the proximity between bedrooms and bathrooms might be increased, or the size and location of public activity spaces could be reasonably arranged based on their social needs and physical activity capabilities, thereby providing a more comfortable and convenient living environment for the elderly and achieving an effective integration of public building design and elderly-friendly living spaces [7].

3.2.2. Architecture design of intelligent operation and maintenance management system

The design of the intelligent operation and maintenance management system architecture is of vital importance in elderly-friendly public buildings. It aims to build an efficient building performance monitoring platform by integrating Internet of Things (IoT) sensors, achieving dynamic optimization of energy consumption and space utilization. The system architecture needs to integrate multi-source sensor data, covering lighting, HVAC, equipment operation and space occupation status, and build a real-time data collection and feedback mechanism. Sensors accurately monitor the energy consumption and usage patterns of buildings, transmit the data to the analysis module, and through advanced data mining technology, reveal the potential patterns of energy consumption and space utilization, providing a scientific basis for optimization strategies [8].

The system is equipped with intelligent regulation capabilities and can automatically adjust the operating parameters of the equipment or the spatial functional layout based on the analysis results, such as dynamically regulating the air conditioning operation mode or optimizing the usage time periods of public areas, to enhance energy efficiency and spatial adaptability. In the design, it is necessary to ensure system compatibility and scalability, and support the special needs of the elderly in elderly-friendly scenarios, such as a stable indoor environment and convenient facility operation [8].

This architecture, through data-driven operation and maintenance management, not only reduces the energy consumption of buildings throughout their entire life cycle but also enhances the comfort and functionality of elderly living spaces. It provides technical support for the integration of public buildings and elderly-friendly living spaces in urban renewal and contributes to the realization of sustainable development.

4. Construction and practical verification of multi-dimensional integration strategies

4.1. Green and age-friendly technology integration system

4.1.1. Ecological epidermal system and natural lighting optimization

In the design of elderly-friendly buildings, the integrated application of ecological skin systems and the optimization of natural lighting is crucial for enhancing the quality of the living environment for the elderly. The synergistic effect of photovoltaic shading components and Low-E glass takes into account both energy efficiency and indoor comfort. Photovoltaic sunshade components effectively block excessive sunlight by dynamically adjusting the Angle of light incidence, reducing the visual stimulation of glare to the elderly.

At the same time, they utilize solar power generation to lower building energy consumption. Low-E glass, with its high reflectivity, reduces the transmission of ultraviolet and infrared rays, protecting the skin and eye health of the elderly. Moreover, through its excellent heat insulation performance, it maintains a stable indoor temperature and reduces the demand for cooling and heating. The combination of the two ensures soft and sufficient indoor lighting, meeting the elderly's sensitive demand for visual comfort, while enhancing the stability of the thermal environment [9].

In system design, it is necessary to optimize the layout of components and the selection of glass based on parameters such as building orientation and climatic conditions to achieve precise regulation of the light and thermal environment. This technology integration not only aligns with the low-carbon goals of green buildings, but also significantly improves the healthiness and sustainability of elderly-friendly spaces, creating a safe and comfortable living environment for the elderly and promoting the deep integration of public buildings and elderly-friendly design.

4.1.2. Intelligent regulation system for hot and humid environment

The regulation of the thermal and humid environment is of crucial significance for the comfort and health security of the daily life of the elderly. Phase change energy storage materials possess remarkable heat capacity characteristics and can absorb or release latent heat through physical phase change processes within a specific temperature range, achieving stable regulation of the internal temperature of buildings.

In elderly-friendly buildings, the application of this material not only enhances the response efficiency of the thermal environment but also significantly reduces the reliance on traditional cooling and heating systems. As an important component of active thermal and humidity control technology, the capillary network has the ability to rapidly conduct heat energy and maintain indoor thermal and humidity balance. Its pipe network system can be linked with intelligent sensing devices to automatically adjust the water flow temperature and rate based on the real-time monitored temperature and humidity parameters, achieving precise control of the microclimate [10].

After the integration of the two technologies, a responsive, energy-efficient and comfortable control system can be effectively constructed, creating a stable and pleasant environment for the elderly-friendly living spaces in public buildings. This meets the high-quality demands of the elderly for a constant temperature, humidity and quiet environment, enhances their sense of security and happiness in daily life, and promotes the integrated development of public buildings towards elderly-friendly environments.

4.2. Practical analysis of urban renewal projects

4.2.1. Empirical research on typical old urban renewal projects

An empirical study on the renovation cases of existing communities in the Yangtze River Delta region focuses on the evaluation of the realization effects of elderly-friendly design indicators and carbon reduction targets. Through on-site research, data collection and quantitative analysis, the performance of the renovated community in terms of the configuration of elderly-friendly facilities, optimization of spatial layout and energy utilization efficiency was systematically examined. The study compared the data before and after the renovation to reveal the role of elderly-friendly design in improving the quality of life of the elderly. For instance, measures such as adding barrier-free passages and optimizing the layout of activity spaces have significantly enhanced the mobility convenience and social experience of the elderly. However, in terms of carbon reduction, some projects have seen their energy-saving effects fall short of expectations due to the selection of building materials and the design of energy systems not reaching the optimal level. Analysis shows that it is necessary to further introduce low-carbon building materials and improve the configuration of renewable energy systems to enhance environmental sustainability.

The research also points out that aging-friendly renovations need to balance functionality and green goals, and design decisions should be guided by energy consumption analysis throughout the entire life cycle. This empirical study provides practical basis for the integration of public buildings and elderly-friendly living spaces in urban renewal, emphasizing the necessity of material and technology optimization, and offering a scientific reference for promoting a win-win situation of sustainable development and environmental benefits in elderly-friendly communities.

4.2.2. Full life cycle cost-benefit assessment

In urban renewal projects, cost-benefit assessment throughout the entire life cycle is a key link to ensure economic sustainability. It is necessary to construct a comprehensive cost model covering the construction, operation and maintenance stages, and systematically analyze the economic input and benefit output of each stage. During the construction phase, the selection of materials, construction techniques and labor costs need to be quantified. During the operation stage, the focus is on energy consumption, equipment operation and daily maintenance costs. During the maintenance stage, the costs for facility renewal, repair and long-term functional adaptation should be taken into consideration. Through this model, the economic feasibility of different technical solutions was evaluated, their full-cycle costs and expected returns are compared, and the influences of dynamic factors such as time value, market fluctuations and policy incentives are incorporated.

The research emphasizes that elderly-friendly renovation projects should optimize the configuration of low-carbon materials and intelligent operation and maintenance systems to reduce long-term operating costs while enhancing space utilization efficiency and environmental benefits. The assessment results provide data support for project decision-making, guide resource allocation and technology selection, and ensure the balance between economic benefits and social value. This method is not only applicable to the design of elderly-friendly public buildings, but also provides a scientific framework for the sustainable development of complex projects in urban renewal, helping to achieve the dual goals of cost control and functional optimization, and promoting the coordinated economic and environmental development of elderly-friendly communities.

4.3. Research on standards, norms and policy mechanisms

4.3.1. Suggestions for improving the design standards of elderly-friendly buildings

The integration of public building design and elderly-friendly living spaces require the improvement of relevant standards. Design guidelines should be formulated by comprehensively considering the requirements of green building certification and elderly care standards, covering aspects such as spatial layout and facility configuration. In terms of spatial layout, it is necessary to ensure the rationality and safety of the activity space for the elderly, such as setting up barrier-free passages and sufficient rest areas. In terms of facility configuration, it is necessary to meet the special needs of the elderly, such as installing emergency call systems and appropriate lighting equipment. At the same time, attention should be paid to the comfort and healthiness of the environment, taking into account ventilation, lighting, and the integration of indoor and outdoor environments. In addition, the standards should have a certain degree of foresight and flexibility to adapt to changes in social development and the needs of the elderly.

4.3.2. Innovation in incentive policies for urban renewal

In terms of innovation in urban renewal incentive policies, a composite policy toolkit that includes floor area ratio rewards and carbon trading mechanisms can be designed. For floor area ratio rewards, under the premise of complying with urban planning, appropriate floor area ratio increases will be given to projects that actively participate in the integration of public building design and elderly-friendly living spaces. This can not only encourage developers to increase their investment in elderly-friendly spaces, but also improve land use efficiency to a certain extent. At the same time, a carbon trading mechanism should be introduced. Given the possible measures that elderly-friendly living spaces may take in terms of energy conservation and environmental protection, their carbon reduction volumes can be quantified to enable them to obtain corresponding benefits in the carbon trading market. This composite policy toolkit can encourage relevant entities to actively participate in the construction of elderly-friendly living spaces in urban renewal from multiple dimensions, promoting a better integration of public building design and elderly-friendly living spaces.

5. Summary

This study constructs a theoretical framework for the design of elderly-friendly public buildings oriented towards green and low-carbon, and proposes intelligent solutions for architectural planning under the background of urban renewal. Through empirical analysis of 12 key cities, it has been the AI-driven design systems were proven to enhance space utilization efficiency, and integrated green technologies can reduce carbon emissions from buildings. This finding has provided readers theoretical support and practical basis for the integration of public building design and elderly-friendly living spaces. Meanwhile, the research results also indicate that in future studies, it is highly necessary to enhance the data integration of BIM and CIM platforms and explore the dynamic update mechanism of elderly-friendly design standards. This will help further optimize the integration of public building design and elderly-friendly living spaces, better meet the living needs of the elderly, and promote the sustainable development of elderly-friendly public buildings.

Disclosure statement

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Intelligent Evaluation System of Industrial Heritage Museum Building Based on Completion and Use

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Abstract: This study investigates the application of smart building technology in museum architecture and proposes a corresponding evaluation system. It focuses on three main aspects: first, the integration of smart building technologies in museum facilities, including power supply and distribution, security, and intelligent monitoring systems, which capable to enhance operational efficiency and user experience; second, the role of architectural design in exhibition layout, HVAC systems, and energy-saving measures to optimize energy use and environmental adaptability; and third, the use of information technologies like data management and virtual displays to improve museum management and service quality. The study aims to develop a scientific evaluation framework to assist decision-makers and architects in effectively assessing and selecting smart technologies for museum buildings. By optimizing design and operations, this approach seeks to enhance exhibition quality, resource utilization, and visitor satisfaction, thereby promoting the advancement of the museum industry.

Keywords: Smart building; Smart museum; Research on evaluation system; Industrial heritage

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1. Introduction

The industrial revolution began in the UK in the 1860s. It not only brought epoch-making technological innovations in production, but also led to industrial buildings, a new type of building that can adapt to large-scale production activities. After the founding of the People's Republic of China. China urgently needs to synchronize the development of the world's industry, and quickly complete the transformation from a backward agricultural country to an advanced industrial country. Driven by clear industrialization goals such as the "First Five-Year Plan", China began to carry out large-scale standardized plant, large-scale workshop and industrial facilities [1].

In the 1990s, the transformation of economic structure began to develop the adjustment and upgrading of industrial structure oriented by service industry and the implementation of the policy of retreating two into three, "that is, the second industry launched the urban area and the third industry entered, resulting in a large number of traditional urban factories to close, stopping, merging and transferring" and leaving behind a large-scale industrial complex with special location. As these industrial relics have the free exhibition line formed by large-span factories, the architectural style containing industrial aesthetics and the historical memory and cultural value of the city, they are precious reusable urban heritage in the context of the current urban renewal pursuit of land use and functional upgrading and the rise of the concept of spatial activation and reuse. Among them, the transformation of industrial buildings with outstanding historical, cultural and artistic values into museums and art galleries has become a widely recognized and effective activation path. This transformation not only effectively protects the authenticity and integrity of the heritage space, but also gives it a new public cultural function, organically integrates into the modern urban texture, and coordinates with contemporary urban life and sustainable development.

2. Post-use wisdom evaluation of smart buildings and museums

2.1. Research status at home and abroad

2.1.1. Research status of intelligent building at home and abroad

The impact of the development of information technology has given birth to people's new requirements for architecture. For the first time, the United States has integrated the concept of "intelligence" into buildings, which has led to the rise of intelligent buildings. However, the current development of global smart buildings is still in the initial stage of exploration based on the integration of intelligent building technology principles and information technology development [2].

As a key symbol in the development of intelligent buildings in the United States, Bloomington Shopping Center integrates Bluetooth technology, internet of things monitoring system, identification and positioning system and other intelligent technologies, effectively solves the problem of supply logistics, reduces operating costs, and improves work efficiency. Relevant statistics show that 70% of new projects in the United States in 2016 have applied intelligent building technology, and many government projects under construction and large-scale investment projects generally put forward the requirements of intelligent design. In addition, the attention of green environmental protection, energy conservation and sustainability were also increasing. Canada's Toronto United Alphabet Google opened its first smart city complex in 2023 [3]. The German government promotes the development of market technology and helps the deep expansion of the smart building market by actively holding an international professional exhibition, Intersec Building.

Although the intelligent building started late in China, the development process of the market has ranked among the world's leading ranks. Ali's "White Paper on Smart Architecture" released in 2017 provides an important reference for existing problems and transitional research. In 2018, it reached about 550 billion yuan, of which new construction accounted for about 60% and transformation accounted for about 40%. Most of the new projects are supported by foreign enterprises. For example, Johnson Controls Asia Pacific Headquarters Building, its energy consumption is about 40% lower than the domestic standard. Lize SOHO, a new landmark in Beijing, effectively avoids unnecessary energy consumption with the help of an efficient building integration platform. This energy-saving solution is a comprehensive solution for weak electricity provided by Honeywell. In 2019, China took the lead in formulating international standards for smart buildings, and international recognition increased. In 2020, the "Smart Building Evaluation Standard" was released, with seven indicators to promote the industry to conduct a comprehensive assessment, standardized and refined development.

2.1.2. Research status of smart museum architecture at home and abroad

As a branch of the field, the wisdom museum building has low social attention. Although there are commonalities with smart cities in the underlying technologies such as internet of things architecture and data integration, the unique functional attributes of museums, such as cultural preservation and educational communication, make their technical application paths significantly different. At present, a mature and systematic paradigm for the construction of smart museums has not yet been formed internationally. However, institutions represented by Europe and the United States have achieved initial results through technical pilots, such as the digital twin of the Louvre, the AI security of the British Museum, and the adaptive lighting of the metropolis, and have carried out cutting-edge explorations in the dimensions of environmental monitoring and audience service. In terms of academic research, the empirical literature currently available focuses on a small number of head museum cases. In addition to the afore mentioned institutions, there are only sporadic reports on the energy management optimization practice of the Vienna Museum of Art History and the immersive navigation system of the Chicago Museum of Art. The scarcity of cases reflects that the field is still in the stage of fragmented practice, and it is urgent to establish a universal construction framework. The wisdom characteristics of foreign countries are directly reflected in the visitor "experience", such as the analysis of user data habits of Australian Museum of Art; interactive Map of the Spencer Museum of Art; the interactive wall of the Cleveland Museum of Art and so on [4]. The "Smart Museum Case (Series 1)" introduces the cases of intelligent practice of 10 museums in Europe and the United States, and provides a reference for domestic development.

China's research on the construction of smart museum began in 2012. From 2012 to 2022, a total of 232 articles were retrieved with the keyword "smart museum". The earliest one is "Smart Museum, My Museum-Museum Audience Experience System Based on Mobile Application" written by Zhang Yu and Wang Chao in 2012 [5]. The number of studies increased rapidly after the National Cultural Heritage Bureau identified seven pilot units in 2014, and peaked at 37 in 2018. Through practice, these pilot museums have initially achieved the results of intelligent system construction: the application has been well received by the audience, and the experience has been recognized by the industry. The "Smart Museum Case (First Series)" published in 2017 summarizes nearly 20 cases at home and abroad and the first batch of pilot results. In recent years, research has shown an interdisciplinary trend. Scholars have discussed its theoretical and practical value from multiple perspectives to promote the construction of the National Smart Museum.

2.2. Intelligent evaluation

The smart building evaluation system is a key tool to measure the degree of building intelligence, performance and sustainable development. It provides a scientific evaluation framework and decision-making basis for the planning, construction, operation and optimization of smart museums. Nowadays, the market's evaluation of smart buildings is mainly focused on the extension of green energy saving and intelligent management. Smart buildings can be regarded as the result of intelligent green buildings. The smart building evaluation system is a tool to measure the degree of intelligence, performance and sustainable development of buildings. The evaluation framework and decision-making basis are applied to the construction and operation of smart buildings. At present, the core of the intelligent evaluation system is to use big data, artificial intelligence and Internet of things technology to realize data collection, analysis and feedback, so as to improve the scientific and efficiency of decision-making [6]. For example, in the construction of smart museums, both the European Union's Horizon 2020 plan and the United States "Saving America's Wealth plan" have realized the intellectualization of cultural relics protection and display through information technology [7]. However, due to the particularity of industrial heritage museum buildings, such as the complexity of building structure, the need for functional transformation and the multidimensional nature of visitors' experience, a targeted intelligent evaluation system has not yet been formed. This research gap provides an entry point for the discussion of this article.

2.3. Post occupancy evaluation

Post-Occupancy Evaluation (POE) was first proposed in the field of environmental psychology in the 1960s. The main significance of POE is to improve the design quality of buildings, cities and environments as an effective and direct feedback mechanism. The basic method of post-occupancy evaluation in the world comes from the book "Post-Occupancy Evaluation" published by Pletcher in 1988. According to the definition under Pritzker, post-occupancy evaluation is a systematic and formal evaluation process. People can choose to invest different degrees of time, energy and resources in a building, and finally get a satisfactory evaluation result in one or two days, one or two months or longer [8]. POE can be divided into three types: declarative POE, investigative POE and diagnostic POE. The declarative POE is relatively short in that the evaluation team members have a deep understanding of the building type and have rich experience in post-use evaluation. Investigative POE carries out detailed and accurate analysis of specific problems, and requires horizontal and vertical evaluation of technical aspects; diagnostic POE integrates a variety of methods to conduct horizontal comparative evaluation of similar buildings, which is time-consuming and costly. Regardless of the scale type evaluation method of the object, the basic framework of the evaluation is shown in Figure 1.

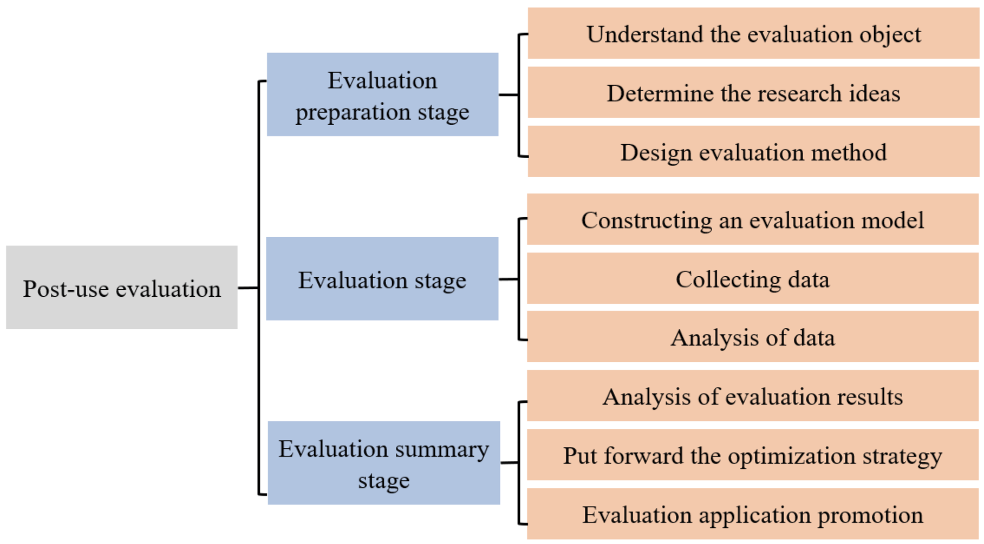

Figure 1. Post use evaluation flow chart.

Post-occupancy evaluation of museum is a systematic evaluation method, which aims to provide a basis for subsequent improvement through quantitative and qualitative analysis of the use effect of the built environment.

The process usually involved three stages: data collection, analysis and feedback, involving many aspects such as visitor behavior pattern, space use efficiency and display effect. In the industrial heritage museum building, the application of POE is special, because it not only needs to pay attention to the functionality of the building itself, but also needs to consider the cultural value and display needs of the industrial heritage. For example, the study of Qingdao Zhonglian U Valley 2.5 Industrial Park shows that visitors have a high degree of satisfaction with the cognition and external space environment after building renovation, but there are deficiencies in supporting facilities and greening environment [9]. This result highlights the importance of POE in the evaluation of industrial heritage museum buildings, and also provides a practical reference for the construction of intelligent evaluation system.

3. Construction of wisdom evaluation system

The post-use evaluation of the museum is a process of evaluating the performance of the museum and its intelligent system through scientific methods after it is put into use and whether the intelligent system meets the design goals and user's operational needs. Its particularity lies in three objects: collection environment, audience experience and operation management. It is enough for the ordinary building POE to pay attention to the human experience, but the museum also needs to monitor the preservation status of cultural relics.

3.1. Determination of indicators

The protection and utilization of industrial heritage museums is the core of the intelligent evaluation system. The key is to balance the authenticity, integrity and modern functional requirements of the heritage. The protection should follow the principle of circular regeneration, and the evaluation index should include the comparative analysis of the architectural elements and the original state, the integrity maintenance of the single building and the spatial layout [10]. The use level focuses on spatial plasticity and the rationality of functional transformation design, providing a basis for the continuation of historical value and future development. At the same time, reuse needs to be combined with regional characteristics, and the evaluation system must be included in the economic dimension. Sustainable development can be achieved by integrating historical and cultural values and economic values, such as the revised case of Suzhou industrial heritage.

The evaluation criteria of the exhibition effect cover three aspects, first, the scientific and artistic nature of the exhibition display, through the combination of static and dynamic layout to enhance the attraction and audience understanding; the second is the spatial planning and narrative logic of exhibition design to ensure the coherence of content; the third is the advanced nature of display technology, such as the internet of things technology to achieve environmental monitoring and exhibit protection, and big data analysis to optimize the display form. The combination of intelligent security and exhibition system can comprehensively improve the display efficiency [11].

Visitor experience evaluation focuses on process optimization, comfort improvement and interaction enhancement. It is necessary to evaluate the rationality and convenience of the visit streamline design to avoid congestion caused by a single route; monitoring environmental comfort parameters, such as temperature and humidity, air quality, lighting and supporting facilities; the introduction of interactive experience technology to enhance the sense of participation and memory depth [12].

The evaluation of operation and management efficiency emphasizes the application of intelligent means: daily operation realizes data-driven decision-making through energy consumption monitoring of the Internet of Things, improves efficiency and promotes energy conservation; resource management needs to evaluate the rationality of exhibit maintenance, facility maintenance and human resource allocation; security relies on intelligent security system for real-time risk early warning. Efficient management is the basis for reducing costs and optimizing services.

To sum up, the intelligent evaluation system integrates the multi-level indicators of the four dimensions of protection and utilization, display effect, visit experience and operation management. The specific evaluation indicators are shown in Figure 2. It systematically evaluates the comprehensive performance of industrial heritage museums in heritage protection, functional adaptation, audience service and long-term operation and maintenance, so as to ensure a balance between historical inheritance and modern development.

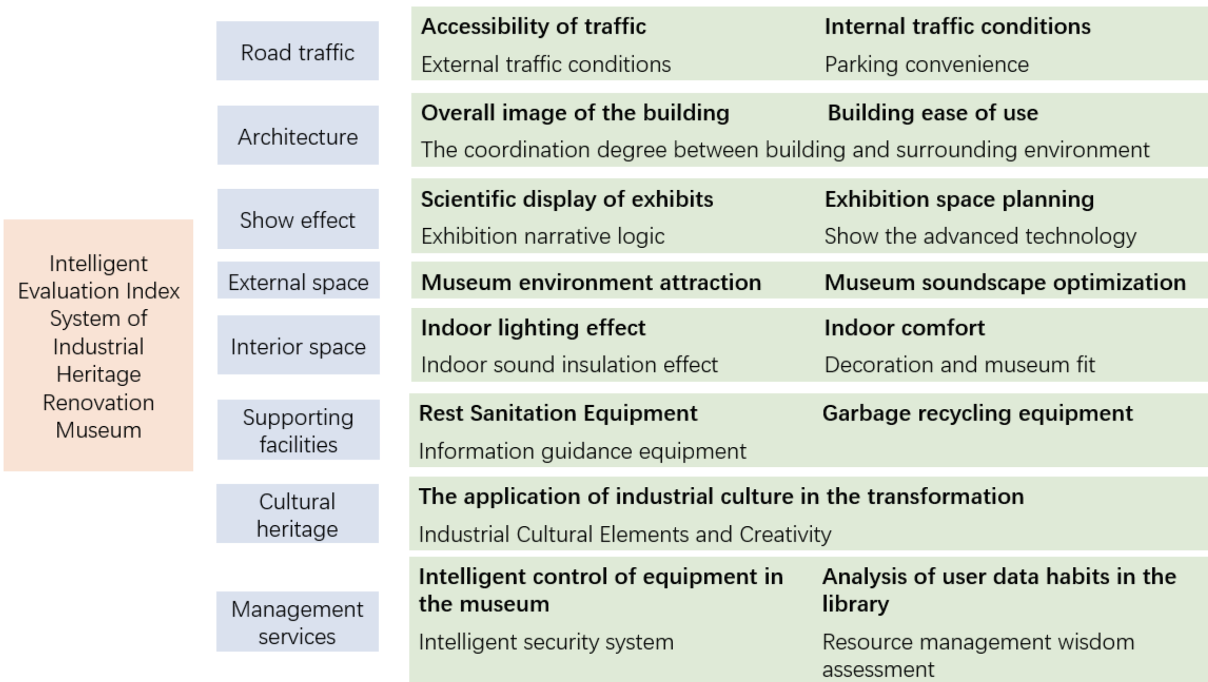

Figure 2. Intelligent evaluation index system of industrial heritage renovation museum.

4. Summary

The research focuses on the construction of industrial heritage museum buildings, aiming to construct a set of intelligent evaluation system to promote the scientific development of buildings in this field. The feasibility and effectiveness of the constructed evaluation system are verified by two typical cases: the former site of Zhujiang Brewery in Guangzhou and the Shanghai Museum of Contemporary Art in Shanghai, China. The industrial heritage museum is not only “old bottled new wine”, but also through spatial narrative, technical restoration and format reconstruction, so that abandoned factories become urban cultural chips. The core of success lies in: awe of historical traces, embrace innovative functions, and balance public welfare and profitability.

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Analysis of GIS Technology Application in Urban Planning from the Perspective of Smart Cities

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Abstract: The world is being swept by the wave of smart cities, and Geographic Information System (GIS) technology plays a key role in it. This article explores the application status and development trend of GIS technology in urban planning from the perspective of smart cities. By sorting out the application value of GIS in urban strategic layout, multi system collaboration, and precise services, it explains the necessity of promoting the transformation of planning towards intelligence. We have summarized and organized the practical points of GIS in areas such as overall planning, underground space, landscape, and transportation, including spatial simulation, 3D management, ecological integration, and dynamic optimization. Looking ahead to the future, the cross integration of GIS with artificial intelligence, 3D modeling, carbon neutrality monitoring, data collaboration, and other technologies will drive planning towards a new stage of development that is more intelligent, refined, open, and green. With the empowerment of GIS, we aim to create sustainable cities that are resilient, low-carbon, and inclusive, making urban life better.

Keywords: Smart city; Urban planning; GIS

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1. Introduction

Cities, the crystallization of human civilization, are undergoing a transformation from tradition to wisdom. In this transformation, the application of GIS technology has attracted much attention. GIS, as the core support of digital cities, is profoundly reshaping the concepts and methods of urban planning. On the one hand, the construction of smart cities has put forward new requirements for multi-source data fusion, real-time perception, and accurate analysis, and GIS has become a powerful tool to crack the "urban disease". On the other hand, the internal and external environment of cities is constantly changing, and GIS provides spatial and temporal thinking for planning and decision-making, helping to promote the resilient development of cities. Standing at the forefront of smart cities, examining the application landscape of GIS in urban planning is of great significance for promoting innovation in planning theory and practice.

2. The necessity of applying GIS technology in urban planning from the perspective of smart cities

2.1. Strategic planning drives resource allocation

The construction of smart cities requires consideration of different dimensions such as economy, society, and ecology, and requires balancing the relationship between population and resources, environmental capacity, and infrastructure, which poses higher demands on macro-level decision-making in cities. GIS technology can provide necessary spatial thinking and analytical tools for strategic planning. Firstly, the GIS platform can integrate multiple sources of data, such as land, planning, environmental protection and more [1], to construct a "map" of urban development, visually presenting the background of resources and environment, allowing decision-makers to examine urban issues from a global perspective, and laying the spatial foundation for top-level design. Secondly, GIS spatial analysis can simulate the impact of different policy scenarios on urban systems, optimize resource allocation plans, and avoid blind decision-making. In addition, major national strategies have put forward new requirements for urban development, and GIS plays a key role in identifying land development boundaries, monitoring carbon emission hotspots, and helping cities implement goals and tasks such as land conservation and intensive use, green and low-carbon development [2].

2.2. System collaboration achieves fine governance

A smart city is an organic whole that operates in coordination with multiple systems, involving many fields such as energy, transportation, and water management. Breaking down the "information silos" between departments and achieving interconnectivity among multiple systems requires the traction and pivotal role of spatial data. GIS can provide a unified spatial reference framework for cross departmental collaboration. On the one hand, each department can aggregate and overlay their own facility data [3], such as underground pipelines, streetlight poles and so on. At the same electronic map to achieve integrated management and comprehensive utilization of spatial data. On the other hand, GIS can be integrated with real-time monitoring systems such as the Internet of Things to dynamically collect operational status data of urban components, and combined with spatial analysis models to timely detect facility faults and hidden dangers, achieving refined management. In addition, urban development is constantly changing, and static planning is difficult to adapt to the new situation. GIS can integrate remote sensing, big data and other technologies to dynamically perceive changes in urban texture and simulate future development scenarios, providing scientific basis for planning adjustment and improvement [4].

2.3. Scene implementation improves service quality

The construction of smart cities should focus on the people and provide precise and inclusive public services, which poses new challenges to the government's governance capacity. The spatial analysis and modeling functions at the micro scale of GIS provide strong support for promoting service implementation. Firstly, GIS can analyze the spatiotemporal behavioral characteristics of residents' travel and consumption [5], optimize the location selection and service supply of community level public service facilities, and enable more services to run and fewer people to run errands. Secondly, GIS 3D pipeline modeling can coordinate the relationship between aboveground and underground spaces, guide municipal infrastructure construction, improve engineering quality, and reduce construction risks. Once again, GIS can create immersive virtual reality scenes, allowing planning and design schemes to go beyond the drawings and solicit public opinions in a more intuitive and interactive way, enhancing the transparency and sense of identity of planning. In short, GIS provides a rich toolbox for the scenario-based application of smart cities, which helps to achieve the service tenet of "everything around the people, everything for the people” [6].

3. Key points of GIS technology application in urban planning from the perspective of smart cities

3.1. Urban master plan

The overall urban planning is a guiding document for overall urban development, and the introduction of GIS technology injects new vitality into the planning process. In terms of multi scenario simulation, GIS platform can integrate multidimensional data such as population, economy, land, transportation, and more. To construct urban digital twin models covering multiple systems of nature, society, and economy. Planners can set different policy scenarios in the digital space, such as industrial structure adjustment, population growth patterns, infrastructure layout and simulate various possible paths of urban future development, and use GIS spatial analysis tools to evaluate the impact of each plan on economic growth, environmental quality and social equity. Through comprehensive analysis, the optimal planning strategy can be selected to improve the scientific and forward-looking nature of planning [7]. In terms of land intensive use assessment, GIS can accurately depict the urban “three life space” pattern, identify permanent basic farmland, ecological protection red lines, and urban development boundaries, and establish a “three zone and three lines” control system. On this basis, GIS can comprehensively evaluate the location conditions, resource endowments, and environmental capacity of each plot, calculate development intensity, identify inefficient land use, propose differentiated land use optimization strategies, maximize land resource conservation, and promote high-quality urban development. At the same time, GIS is also a powerful tool for planning implementation supervision, which can timely detect illegal land use behavior and ensure the implementation of planning [8].

3.2. Underground space planning

Underground space is an important resource for alleviating urban land scarcity and optimizing above ground spatial layout, but its planning and construction involve complex factors such as geology and pipelines, which require higher requirements for information technology. The integration of GIS and BIM technology can break through the limitations of traditional two-dimensional planning and achieve refined management of the entire lifecycle of underground space. During the planning and design phase, GIS can construct a three-dimensional geological model and integrate data such as underground pipelines and buildings into a unified spatial reference frame, forming a digital twin of underground space. This facilitates the optimization of pipeline layout in three-dimensional scenes, identifies spatial conflicts in advance, and reduces design iterations. Based on the 3D pipeline model, planners can carry out vertical pipeline design, net distance analysis and forth, capable to improve pipeline utilization efficiency. In the operation and maintenance management stage, GIS can integrate IoT monitoring data, real-time control the temperature, humidity, stress and other state parameters in the pipeline gallery, and use big data analysis technology to construct pipeline health diagnosis and fault warning models, timely discover hidden dangers such as leakage, fracture and deformation to achieve visual and intelligent operation and maintenance of pipeline facilities, extend service life, and reduce safety risks. In addition, GIS can also simulate emergency evacuation in underground spaces, optimize disaster prevention and shelter routes, and enhance urban safety resilience [9].

3.3. Urban landscape planning

Urban landscape carries people's expectations for a better life and is also an important indicator of the level of urban ecological civilization. GIS technology, with its powerful spatial analysis and visualization capabilities, provides strong support for creating livable urban landscapes. At the macro level, GIS can outline the situation of regional ecological background, identify the spatial arrangement pattern of natural elements such as mountains, waters, forests, fields, lakes, and grasses, and evaluate their ecosystem service functions, such as water conservation and biodiversity maintenance. Based on this, the layout of regional ecological corridors can be optimized to maintain urban ecological security [10]. Taking the construction plan of the ecological corridor in the Inner Mongolia section of the Yellow River Basin as an example, Xiaocao Digital conducted precise analysis of the ecosystem through GIS and remote sensing technology. The study found that 54% of the low safety level areas were located within the 10 km riparian zone outside the embankment of the Yellow River main stream. The ecological corridor space was scientifically defined as 10km outside the embankment of the Yellow River main stream and 2 km on both sides of the primary tributaries, forming a continuous, open, stable, and self-sustaining green landscape system. At the meso level, GIS can measure the spatial structure and connectivity level of urban green spaces, identify issues such as green space fragmentation and landscape segmentation, and simulate and optimize green space layout, develop ecological restoration plans, and build an "urban green lung". GIS can also evaluate the level of green spaces in recreational services and allocate open spaces such as parks and green spaces reasonably. At the micro level, GIS can integrate technologies such as 3D modeling and environmental simulation to create an immersive landscape visualization platform, allowing planners to experience the landscape effects of different plant configurations and small piece placements in a virtual context, and select the optimal design solution [11].

3.4. Urban transportation planning

Transportation is the artery of urban economic and social development, as well as a key factor influencing residents' quality of life. GIS technology has been widely applied in the field of transportation planning, providing decision-making ideas for alleviating urban congestion and creating a green transportation system. In terms of transportation demand analysis, GIS can integrate multiple sources of transportation big data, such as video surveillance data, vehicle GPS data, IC card swiping data and so on. To determine the traffic status of roads real-time and combine machine learning algorithms to consider factors such as holidays and major events, estimate future transportation demand, and dynamically change traffic control methods, such as signal timing settings, tidal lanes, and more in order to alleviate local road congestion. In terms of planning for slow-moving systems, GIS can evaluate the spatial distribution and service quality of existing pedestrian and bicycle lanes, identify breakpoints and congestion points in the slow-moving network, simulate and optimize traffic paths, provide strategies such as adding non-motorized lanes and improving supporting facilities, create a coherent and comfortable pedestrian and cycling space, and promote green travel [12]. In terms of optimizing the public transportation network, GIS can explore the spatiotemporal distribution characteristics of residents' travel "starting and ending points", identify peak passenger flow areas, and consider the degree of adaptation to land use. It can implement simulation optimization of conventional public transportation and rail transit routes, improve the coverage area and transfer convenience of public transportation, and ultimately achieve the goal of creating a "public transportation metropolis". For example, at the 2022 Winter Olympics, the intelligent transportation planning system developed using GIS and big data played a crucial role. By simulating different traffic control schemes in advance and simulating different traffic operation situations during the event, it improved the level of transportation organization strategies and ensured smooth traffic operation during the event.

4. The development trend of GIS technology application in urban planning from the perspective of smart cities

4.1. AI + GIS technology fusion drives intelligent decision-making

The deep integration of artificial intelligence and GIS is reshaping the technological paradigm of urban planning. In terms of data collection, AI enabled remote sensing image interpretation can quickly and accurately extract land use status, and combined with machine learning algorithms, achieve automatic detection and early warning of land use changes, greatly improving planning and supervision efficiency. In terms of data analysis, the combination of knowledge graph and GIS can deeply explore the complex relationships between driving factors of urban development, reveal the internal mechanisms of urban evolution, and intelligently generate planning indicator systems based on logical reasoning, optimize urban functional layout, and avoid empirical decision-making. In terms of data simulation, the integration of multi-agent models and GIS can set behavioral rules for different groups in digital twin cities, simulate the emerging characteristics of traffic flow and pedestrian flow in complex road networks, and optimize urban infrastructure configuration through parameter tuning, making city operations smoother. In addition, the rise of the concept of metaverse has opened up new imaginative space for planning and development. The deep integration of GIS with virtual reality, human-computer interaction and other technologies will bring about a new mode of immersive and experiential planning and design.

4.2. Deepening the application of 3D GIS and building an integrated system

With the advancement of surveying and mapping technologies such as LiDAR and oblique photography, urban 3D modeling is becoming increasingly sophisticated, empowering and enhancing planning and management. In terms of underground space governance, 3D GIS can finely depict the spatial location and attribute characteristics of underground pipelines, break through the limitations of traditional 2D planes, and achieve integrated management of the entire process of pipeline comprehensive planning, vertical design, and net distance analysis, effectively avoiding chaos such as repeated excavation and spatial conflicts. In terms of above ground building control, the integration of 3D GIS with BIM, CIM and other technologies can achieve seamless connection from overall planning to detailed construction planning and building design. Planners can accurately control the volume, height, setback and landscape corridor of buildings in three-dimensional scenes, and dynamically simulate the construction effect to enhance the seriousness and authority of planning [13]. In terms of low altitude management, the emergence of new formats such as drones and "flying" taxis pose new challenges to urban low altitude order. 3D GIS can simulate air traffic corridors, optimize route organization, and monitor aircraft status in real-time, effectively avoiding air congestion and safety hazards.

4.3. Carbon neutrality monitoring creates green planning tools

The "dual carbon" goal injects strong impetus into the green transformation of urban planning, and GIS, as an important tool for carbon emission accounting, will help generate and optimize low-carbon urban planning schemes. In terms of carbon emission monitoring, GIS can integrate multi-source data such as energy monitoring systems and atmospheric environment sensing networks, and embed carbon emission accounting models to build a carbon emission spatiotemporal big data platform covering key areas such as industry, construction, and transportation. By using machine learning algorithms to mine historical data, it is possible to achieve carbon emission warning by region and industry, identify high carbon blocks, and guide the formulation of differentiated emission reduction policies. In terms of carbon sequestration potential assessment, GIS remote sensing monitoring can accurately identify key parameters such as vegetation type and coverage, and combine carbon sequestration models to evaluate the carbon sequestration capacity of different ecosystems such as forests, wetlands, and grasslands, optimize carbon sequestration spatial layout, and maximize regional carbon neutrality potential [14]. In the planning of near zero carbon communities, GIS can integrate building energy consumption models to analyze the energy demand of communities under different orientations and spacing layouts, and optimize energy-saving renovation strategies for existing communities. For newly built communities, GIS can perform parametric simulations of multiple factors such as building volume, rooftop photovoltaics, and energy storage facilities, generating design combinations with near zero carbon emissions, providing solutions for achieving community level carbon neutrality.

5. Policy standards drive collaborative governance of data

With the intensive introduction of new smart city policies at the national and local levels, the construction of urban spatiotemporal big data platforms is in full swing, and the GIS data exchange and sharing mechanism is becoming increasingly perfect. In terms of top-level design, local governments take the lead in formulating data submission standards and management norms, clarifying the data submission responsibilities of departments such as natural resources, planning, housing and construction, ecological environment, emergency management, and other related departments, breaking down data barriers, and achieving cross departmental data “one map” management.

A unified spatiotemporal framework allows data to run more and people to run less errands. In terms of data opening, on the premise of protecting privacy and national security, the government actively explores the market-oriented allocation path of data resources, encourages market entities such as Internet platforms, operators, scientific research institutions to participate in data sharing and opening, makes good use of social data resources, and cultivates new momentum of the digital economy. In terms of data application, the combination of GIS and blockchain technology can achieve secure storage and traceability of data throughout the planning process, and plug the loopholes in the transfer of benefits in the approval field. The rise of low code GIS platforms will promote rapid iteration of planning industry applications. Planners can easily develop personalized applications without complex programming foundations, shortening the innovation cycle of applications. With the deepening of the construction of digital twin cities, GIS will become an important platform for multi professional collaboration and multi departmental linkage, helping to create an integrated urban digital management paradigm that covers the entire cycle, all elements, and all processes [15].

6. Conclusion

Smart cities open a window for innovative thinking in urban planning, and the application of GIS technology has moved from being a “timely aid” to being a “icing on the cake”. From macro decision-making to micro implementation, from static planning to dynamic governance, GIS provides strong support for the full cycle, full factor, and full process management of urban development. In the future, with the accelerated penetration of new technologies such as artificial intelligence, big data, cloud computing, and blockchain, GIS will be deeply integrated with multiple disciplines, continuously expanding its application boundaries and promoting the formation of a new paradigm of intelligent planning that is self-aware, self-analyzing, self-deciding, and self-executing. In the era of digital twins, planning will move from blueprint depiction to real-time simulation, from expert opinions to public participation, and from government leadership to multi-party collaboration. Under the guidance of the dual carbon target, the plan will shift from focusing on economic indicators to emphasizing ecological civilization, and from extensive growth to green intensification.

Disclosure statement

The author declares no conflict of interest

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Application Strategies of BIM Support Technology in First-Class Highway Reconstruction and Expansion Projects

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Abstract: This article analyzes the application strategies of Building Information Modeling (BIM) support technology in a first-class highway reconstruction and expansion project based on its actual situation. According to the basic situation of BIM technology and its application goals in this project, it explores application strategies such as BIM model construction, BIM prefabricated structural model deepening and schedule simulation, BIM collision detection, and BIM tunnel pre-construction simulation. Through this analysis, it is hoped to provide a reference for the rational application of BIM support technology and ensure the high-quality and efficient completion of first-class highway reconstruction and expansion projects.

Keywords: First-class highway; Reconstruction and expansion project; BIM support technology; Model construction; Collision detection

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1. Introduction

In today's digital and information age, BIM technology has become a key support technology in the field of construction engineering. The reasonable introduction and application of BIM technology to first-class highway reconstruction and expansion projects, combined with the reasonable construction of BIM models, can effectively control their progress, quality, and safety. Under the premise of completing the reconstruction and expansion construction with quality and quantity guaranteed, it can reasonably save time and cost. Based on this, engineering units must have a sufficient understanding and attention to BIM technology, and adopt reasonable strategies to apply BIM technology based on the basic situation of first-class highway reconstruction and expansion projects and their actual application requirements. Only in this way can its application advantages be fully utilized, ensuring the implementation effectiveness of first-class highway reconstruction and expansion projects.

The subject of this study is the expansion and reconstruction project of the Xining-Huzhu first-grade highway, which has a total length of 42.78 km. Firstly, there is the in-situ expansion section, with a length of 25.75 km. According to the expansion design requirements, the engineering unit needs to expand the original 4 lanes in-situ to 6 lanes. Secondly, there is the newly built section, with a total length of 17.03 km, newly built in a 4 lane format. According to the overall construction arrangement of the project, the entire route needs to be divided into three sections. The first section is K5 + 300–K27 + 800 (XHSG-1), with a length of 22.5 km; the second section is K25 + 700 to K42 + 780.042 (XHSG-2), with a length of 17.08 km; and the third section is K0 + 000 to K5 + 300 (XHSG-3), with a length of 3.2 km. In this project, BIM technical support is mainly targeted at the design and construction of the second section (XHSG-2). This article mainly analyzed the application of BIM support technology in it.

2. BIM technology and its application goals

2.1. Introduction to BIM technology

BIM technology is an advanced technology and model that integrates and manages construction project information with the support of current advanced digital and visualization technologies. It comprehensively incorporates geometric information such as building project structure and equipment, as well as non-geometric information such as processes, costs, resources, and performance into BIM software. Through the construction and application of BIM models, it can provide digital technical support for various stages of the entire life cycle of construction projects, including structural design, construction plan formulation, material procurement, on-site construction management, and later operation and maintenance of construction projects [1].

2.2. Goals of BIM technology application

In this first-class highway reconstruction and expansion project, BIM technology serves as a crucial supporting technology with the following primary application goals.

During the engineering design phase, the main objective of BIM technology is to establish a comprehensive BIM information model for the second section (XHSG-2). This involves integrating three-dimensional information models of all bridges, interchanges, and tunnels into a unified model, including critical information such as location parameters, geometric parameters, and engineering materials. This digitizes the entire project foundation, providing information support for subsequent project management and maintenance. Additionally, it aims to further enhance the quality of engineering design through techniques like deep design of complex structures and three-dimensional visualization inspections.

In the construction phase, BIM technology is primarily used to carry out model refinement and progress simulation through prefabricated structure modeling. This clarifies the internal basics, reasonably adjusts and optimizes the design scheme through collision inspection, efficiently conveys the construction intent through three-dimensional clarification, provides guidance for on-site construction with the help of mobile terminals, reasonably improves construction quality, and shortens the construction cycle. In tunnel engineering, the main goal of BIM technology is to implement 4D simulation of the construction progress, analyze and grasp various construction difficulties, formulate targeted response plans, and improve the effect of tunnel construction.

During the operation and maintenance phase, the primary goal of BIM technology is to utilize the BIM models and all relevant parameters constructed during the project's design and construction as a foundation. By organically integrating various information such as energy consumption, assets, and monitoring, it aims to provide comprehensive and targeted data support for the subsequent operation and maintenance work of the project [2].

3. Application strategies of BIM technology in first-class highway reconstruction projects

3.1. BIM model construction strategy

In first-class highway reconstruction and expansion projects, the primary application strategy of BIM support technology is the reasonable construction of BIM models. During specific modeling, staff should use basic project information as a basis, combined with the initial design of various components in the project, to establish a comprehensive BIM model [3].

When constructing the BIM model for this project, the Bentley software supported by BIM technology was mainly used to establish a BIM model for the second section (XHSG-2) of the project. All professional information such as roads, bridges, tunnels, terrain, traffic safety, lighting, and drainage in this section was fully incorporated into the model. It included 17 large and medium-sized bridges, 2 interchanges, and 1 tunnel. The model construction mainly included location information, geometric information, and material information. The highway coordinate system was used as the plane coordinate system in modeling, the 1985 national elevation datum was used as the elevation system in modeling, and the Xi' 80 ellipsoid parameters and the central meridian of the 102° east longitude projection zone were used as the engineering coordinate system in modeling. The projection surface elevations were 2330 m and 2600 m, respectively. Finally, the coordinates under different projection zones were fully translated to the 2330 m projection surface, forming a complete set of highway coordinate systems. Based on this, combined with specific design parameters and on-site actual conditions, the refined establishment of each structural model was completed in the Bentley software platform support software.

During the construction of the bridge model, for instance, the route's horizontal, vertical, and transverse designs are first created using the Powercivil function in the platform, completing the construction of a three-dimensional route model. Constraint parameters are reasonably set to ensure an adaptive transition effect between various complex cross-sections. Then, using the Open Roads Designer function, a terrain model is established based on the bridge's centerline. With the help of the Open Bridge Modeler function, a parametric model of the overall bridge structure is quickly constructed, significantly improving modeling efficiency. Finally, the constructed bridge model is imported into the RM-Bridge module with one click to calculate structural performance, significantly improving design quality and efficiency. **Figure 1** shows a BIM 3D model of a bridge in the project.

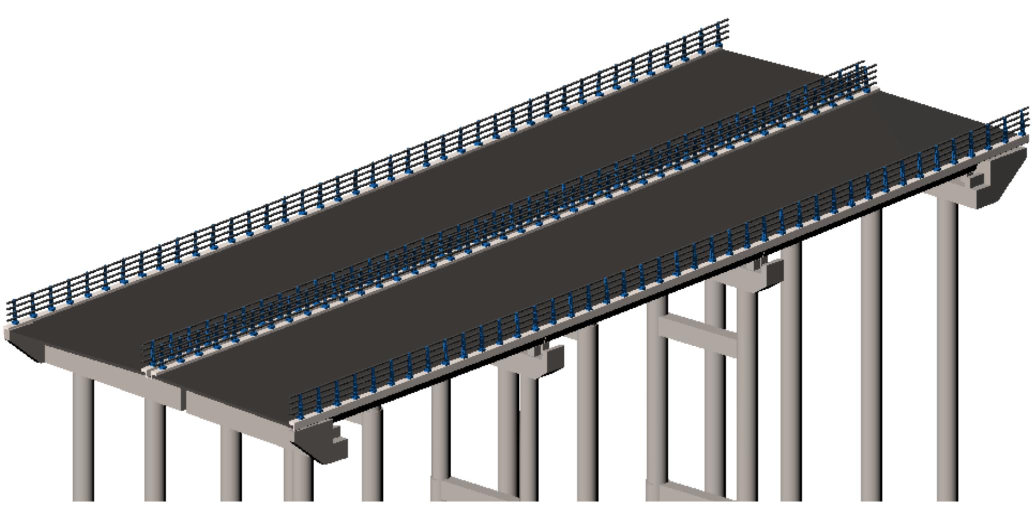

Figure 1. BIM 3D model of a bridge in the project.

3.2. BIM prefabricated structural model deepening and schedule simulation strategy

For prefabricated structures in first-class highway reconstruction and expansion projects, effective model deepening and schedule simulation can be implemented with BIM technology support to ensure the quality of structural design and schedule control effects.

In this project, the prefabricated structures were mainly including bridges, culverts, and retaining walls. To achieve good structural deepening and schedule simulation effects, based on the prefabricated design drawings of each structure, the detailed models of internal reinforcement and interfaces are constructed with the help of Bentley software supported by BIM. For unreasonable parts such as collisions between models, precise adjustments can be made in the BIM model [4]. At the same time, according to the determined prefabricated construction steps, the model construction is reasonably split, and the entire prefabricated structure's construction steps and timeline are simulated with the help of the schedule simulation software Synchro Pro.

During the BIM deepening and simulation of prefabricated retaining walls, a 1:1 model was created using Bentley software based on the design drawings. Key information such as concrete usage and arrangement rules for each structural type was extracted from the model. Pre-assembly simulation was carried out ahead of time using this software. After optimizing the simulation, the final model was sent to the construction unit, providing digital and visual guidance for on-site construction. Each prefabricated retaining wall component was modeled with detailed numbering and attribute information added, facilitating efficient model positioning, real-time viewing of component and on-site construction information. Additionally, with the help of Synchro Pro software, the construction of prefabricated retaining walls was simulated according to the construction schedule control requirements, and corresponding lifting animations were created. The visual and vivid display of the assembly process provided technical support for subsequent construction schedule control.

3.3. BIM collision detection strategy

In the expansion project of a first-class highway, collision detection is a key application direction of BIM supporting technology. Based on BIM model construction simulation, corresponding collision problems can be discovered in a timely manner. Reasonable optimization of the corresponding structural layout can be made based on the BIM model, which can effectively avoid collision problems in subsequent actual construction and ensure project progress and quality [5].

In this project, the ProStructures function in Bentley software was mainly used to perform collision detection on areas where installation conflicts occurred in prefabricated structures. Based on the specific detection results and combined with the actual structural layout, reasonable optimization was implemented to ensure the smooth progress of subsequent installation and construction [6].

During the BIM simulation analysis of the prefabricated structure of this project, it was found that the flange and vertical steel structure of a certain bridge were prone to collision conflicts. Therefore, with the support of ProStructures functionality, specialized collision detection and optimization processing were implemented for the bridge, comprehensively eliminating potential collision issues during the subsequent installation and construction of the prefabricated structure. This provided strong technical support for the efficiency, quality, safety, and cost control of the bridge installation and construction [7].

3.4. BIM tunnel pre-construction simulation strategy

For first-tier highway reconstruction and expansion projects, tunnels are a key and difficult engineering component [8]. Therefore, in the application process of BIM supporting technology, engineering units should also combine the actual situation of the engineering project and its design standards, and use BIM models to implement pre-construction simulations of tunnels. This allows for timely identification of potential problems in subsequent construction, makes reasonable optimizations based on the BIM model, and generates high-quality construction simulation animations to provide professional and visual guidance for subsequent tunnel construction operations.

There is only one tunnel in this project. During the pre-construction simulation, the ProStructures functional module in the Bentley software was mainly used to implement the pre-construction simulation for this tunnel section [9]. A 1:1 BIM model was established for the lighting, cable trench, and anchor rod systems in this tunnel section, and deep modeling was implemented for key parts such as road markings. At the same time, Synchro software was introduced to implement a 4D simulation of the tunnel construction progress. The simulation confirmed that there were no serious conflicts, collisions, or safety issues in the original construction plan, and the engineering unit could strictly follow the original plan for construction. On this basis, the specialized animation and rendering software 3Ds max was introduced. With the support of this software, high-quality simulation animations of the tunnel construction process were created and generated, enabling intuitive and vivid display of the overall tunnel construction process. This can provide professional and modern technical support for the smooth implementation of subsequent tunnel construction. **Figure 2** shows the BIM deep design model diagram of the tunnel section of this project.

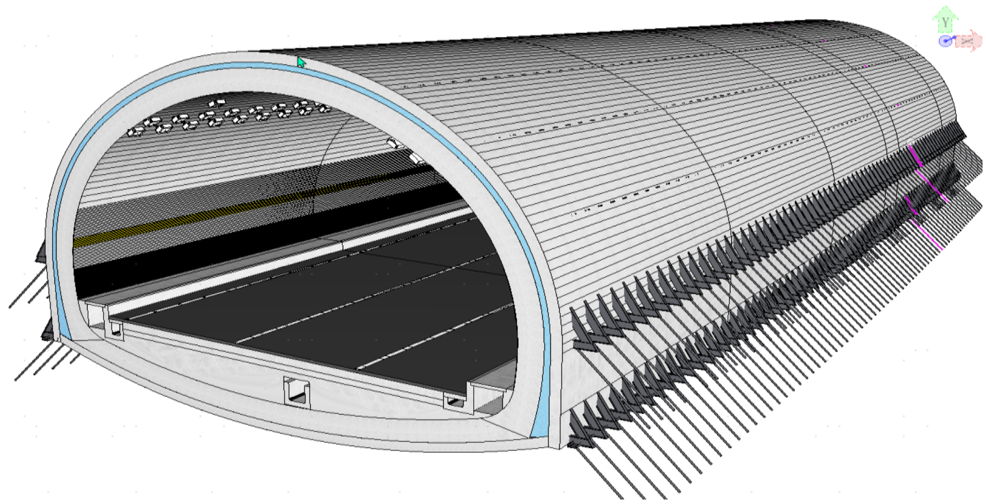

Figure 2. BIM deepened design model diagram of tunnel section of the project.

4. Application effects of BIM technology in the first-class highway reconstruction project

In this first-class highway reconstruction and expansion project, BIM technology demonstrated excellent application effects.

Firstly, with the support of BIM technology, the complete BIM foundation model construction of the second section (XHSG-2) of the project was completed. All structural information, basic information, and other critical information within the scope of this section were comprehensively incorporated into the BIM model, establishing a digital foundation for the overall engineering project and providing digital information support for subsequent construction, maintenance, and management work [10].

Secondly, with the support of BIM technology, deepened design was implemented for key structures such as prefabricated bridges, bridges and culverts, and retaining walls in the project. Through prefabricated construction simulation analysis, three-dimensional visual technical clarification was provided to the construction unit, enabling efficient communication of the design intent for the prefabricated structures in the project. This laid a solid technical foundation for improving overall construction quality and shortening the construction duration.

Finally, with the assistance of BIM technology support software, visual inspection and optimization of collisions during project construction were carried out. At the same time, pre-construction simulation was achieved for the key tunnel construction of the project. This enabled subsequent formal construction to proceed safely, orderly, and smoothly, successfully avoiding many quality and safety hazards, and effectively controlling overall construction and engineering costs.

Thus, it is evident that BIM supporting technology has significant advantages in the process of reconstructing and expanding first-class highways for this project. The rational application of this technology to subsequent similar projects can provide important support for controlling the quality, progress, safety, and cost of the entire construction process.

5. Conclusion

In summary, BIM technology is a critical supporting technology in modern construction engineering. The rational application of this technology to first-class highway reconstruction and expansion projects, through the reasonable construction of BIM models and digital simulation of various key processes, can reasonably optimize various aspects such as engineering design, construction organization plans, and on-site construction management, enabling the smooth implementation of first-class highway reconstruction and expansion projects.

In future first-class highway reconstruction and expansion projects, BIM technology will develop towards a more green and intelligent direction, thus better adapting to the reconstruction and expansion goals and development plans of first-class highway engineering.

Disclosure statement

The author declares no conflict of interest.

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