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A Review of the Application of Low-Carbon Concepts in Civil Engineering Structural Design

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Abstract

Against the background of global warming and China's "Dual Carbon" strategy, the low-carbon transformation of the civil engineering industry has become imperative. As a critical stage in the whole life cycle of engineering projects, structural design serves as an important approach to achieving carbon emission reduction. This paper systematically reviews the connotation of the low-carbon concept and its integration paths with structural design, summarizes key technologies including low-carbon building materials, innovative structural systems, and efficient energy utilization, and analyzes their application effects based on typical engineering cases. In view of existing challenges in technology, economy, policy and public awareness, countermeasures are proposed for the future intelligent, standardized and industrialized development. The results show that integrating low-carbon concepts into structural design can effectively reduce life-cycle carbon emissions, which is of great significance for promoting the green and sustainable development of civil engineering and supporting the achievement of the "Dual Carbon" goals.

Keywords

Low-carbon Concept, Civil Engineering, Structural Design, Life Cycle.

1. INTRODUCTION

In recent years, global warming has been worsening, and green low-carbon development has become a global consensus[1]. China has put forward the strategic goals of carbon peaking and carbon neutrality, forcing high-energy-consuming industries to transform to low-carbon. As a pillar industry of the national economy, civil engineering has high energy consumption and carbon emissions in its entire life cycle, making it a key field to achieve the "Dual Carbon" goals.

Structural design, as the source of the project life cycle, directly determines the carbon emission level of projects. However, traditional structural design focuses on safety, applicability and economy, ignoring low-carbon environmental protection, which cannot meet the green development requirements of the new era. Integrating low-carbon concept into the whole process of structural design has become an inevitable choice for the high-quality development of the industry[2].

At present, developed countries such as Europe, America and Japan have established a complete technology and standard system for low-carbon structural design. Although relevant research in China is advancing, there are still problems such as imperfect technology, inconsistent standards, high costs and insufficient low-carbon awareness[3]. Therefore, this paper reviews the application of low-carbon concept in civil engineering structural design, sorts out core theories and technologies, summarizes domestic and foreign application status, analyzes problems and puts forward countermeasures, so as to provide reference for industry low-carbon transformation, engineering practice and policy formulation, and promote the green and sustainable development of civil engineering.

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2. PRELIMINARY STUDY

2.1. Research Background

In recent years, the issue of global climate change has become increasingly severe. Excessive greenhouse gas emissions have resulted in frequent extreme weather events and a continuous deterioration of the ecological environment. Consequently, controlling carbon emissions and promoting low-carbon development have emerged as a global consensus. At the 75th session of the United Nations General Assembly, China officially put forward the strategic goals of achieving carbon peaking by 2030 and carbon neutrality by 2060[4]. These objectives impose stringent emission reduction requirements on all energy-intensive industries.

The civil engineering industry encompasses a wide range of sectors, including buildings, bridges, tunnels, and municipal engineering. Throughout its entire life cycle — from the production of building materials, structural design, and construction to operation, maintenance, demolition, and recycling — this industry consumes nearly 40% of the global energy and accounts for more than 30% of the nation's total carbon emissions[5]. As such, it constitutes a key field that must be strictly regulated to achieve the "Dual Carbon" goals.

Traditional structural design in civil engineering often places excessive emphasis on the safety, serviceability, and economy of structures, while neglecting carbon emissions, resource consumption, and ecological environmental protection. This has led to prominent issues such as the waste of building materials, high construction energy consumption, and significant operational carbon emissions.

With the popularization of the concepts of green building and sustainable development, and the successive introduction of national policy documents like the Assessment Standard for Green Building and the Implementation Plan for Carbon Peaking in the Urban and Rural Construction Sector, promoting the low-carbon transformation of civil engineering structural design has become a core direction for industrial development. Against this background, a systematic investigation into the application paths, technical methods, and practical effects of low-carbon concepts in structural design is of great practical significance for addressing the industry's high carbon emission challenges and implementing the national low-carbon strategy.

2.2. Research Significance

2.2.1 Theoretical Significance

At present, low-carbon research in China’s civil engineering sector mainly focuses on the construction stage and the development of building materials[6]. Systematic research on low-carbon applications in the structural design phase is relatively insufficient, and a complete theoretical system and application framework has not yet been established.

By clarifying the internal relationship between low-carbon concepts and civil engineering structural design, this paper integrates existing low-carbon structural design technologies and practical experience, supplements and improves the theoretical content of low-carbon design in civil engineering, and identifies the core points of carbon emission reduction in the structural design stage.

It provides a theoretical reference for subsequent relevant academic research, enriches the research dimensions of green civil engineering, and promotes the in-depth integration of low-carbon design theory with professional theories of structural design.

2.2.2 Practical Significance

The low-carbon structural design technologies, case experiences and optimization strategies summarized in this paper can directly provide practical references for structural design engineers and construction enterprises.

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They help to optimize structural schemes, select low-carbon building materials and innovate structural systems at the project design stage, so as to reduce carbon emissions and resource consumption of engineering projects from the source.

Meanwhile, the research results can provide a basis for industry authorities to formulate low-carbon design codes and incentive policies, promote the large-scale application of low-carbon technologies in civil engineering, and help the civil engineering industry break away from the development model of high energy consumption and high emissions.

This will facilitate the green and sustainable development of the industry and effectively support the implementation of China’s "Dual Carbon" goals.

2.3. Literature Review

2.3.1 Research Status Abroad

In developed countries abroad, research on low-carbon civil engineering started relatively early and has resulted in relatively mature technical systems and policy standards. Countries such as those in Europe, the United States, and Japan took the lead in proposing the concept of life cycle assessment (LCA) for carbon emissions, integrating it into the core process of structural design, and establishing comprehensive systems for calculating carbon emissions of building materials and evaluating the low-carbon performance of structures[7].

In terms of technological research and development, Germany has focused on promoting prefabricated steel structures and recycled concrete technologies, as well as developing high-performance low-carbon building materials, significantly reducing material-related carbon emissions in building structures[8]. Japan, considering its own geological conditions, has developed lightweight low-carbon structural systems and integrated seismic design with low-carbon design to achieve both structural safety and low-carbon emission reduction[9]. The United States relies on BIM technology and digital twin technology to realize carbon emission simulation and optimization throughout the entire structural design process, precisely targeting emission reduction points at the design stage[10].

In addition, foreign countries have issued strict low-carbon building regulations and carbon trading policies, which mandate low-carbon design for engineering projects and promote the wide application of low-carbon technologies in large-scale civil engineering. This has formed a coordinated development model integrating "technology, policy, and market".

2.3.2 Research Status in China

In recent years, China has carried out extensive research on the low-carbon development of civil engineering, and has made remarkable progress in the research and development of low-carbon building materials, prefabricated structural design, green construction technologies and other fields[11].

Domestic scholars have conducted in-depth studies on the performance and application of low-carbon materials such as high-performance concrete, low-carbon steel bars and recycled aggregate building materials, verifying their feasibility in structural design.

Low-carbon structural systems including prefabricated concrete structures and modular steel structures have been gradually promoted and applied in residential and public buildings, effectively reducing material waste and carbon emissions during the construction stage.

At the same time, China has begun to establish life-cycle carbon emission accounting models for civil engineering and apply BIM technology to the optimization of low-carbon structural design.

However, compared with developed countries, there are still many deficiencies in China’s low-carbon structural design.

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First, the low-carbon design codes and evaluation systems are imperfect, and there is a lack of unified carbon emission accounting standards.

Second, bottlenecks exist in the performance and large-scale production of low-carbon building materials, leading to relatively high costs.

Third, structural designers have insufficient low-carbon awareness, and the integration of low-carbon technologies with traditional design is inadequate.

Fourth, the concept of life-cycle low-carbon design has not been fully popularized. Most projects still focus on emission reduction during the construction stage, ignoring control at the design source.

2.3.3 Research Review

Overall, foreign countries have formed mature theories, technical and policy systems in the field of low-carbon structural design, with a wide range of practical applications and significant emission reduction effects. Their life-cycle low-carbon design concepts and technological innovation experience are worthy of reference for China.

Although China has achieved certain research results in the field of low-carbon civil engineering, it is still generally in the initial stage. Most studies focus on a single technology or a single link, lacking systematic application reviews and whole-process design frameworks. Based on existing research results, this paper compensates for the lack of systematic research on low-carbon structural design in China, comprehensively sorts out application technologies, current status, problems and trends, and provides a more comprehensive reference for industrial practice.

2.4. Research Contents and Methods

Firstly, this paper expounds the theoretical basis of the low-carbon concept and civil engineering structural design, and clarifies the core logic of their integration.

Secondly, it analyzes the application principles and key technologies of the low-carbon concept in civil engineering structural design, covering low-carbon building materials, structural systems, energy coordination and other aspects.

Then it sorts out the application status at home and abroad, and analyzes the application effects combined with typical cases.

Furthermore, it summarizes the existing problems and challenges in current applications.

Finally, it puts forward development countermeasures and future trends, forming a complete research system.

3. THEORETICAL BASIS OF LOW-CARBON CONCEPT AND CIVIL ENGINEERING STRUCTURAL DESIGN

3.1. Low-carbon Concept and Core Connotation

The low-carbon concept originated from environmental protection needs in response to global climate change. Its core is to reduce fossil energy consumption and lower greenhouse gas emissions (mainly carbon dioxide) through technological innovation, institutional optimization, and conceptual renewal, so as to achieve coordinated win-win results between economic and social development and ecological environment protection[12].

Its core objectives are low energy consumption, low emissions, and low pollution. It pursues the efficient utilization and recycling of resources, balancing current development with long-term ecological protection.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202604_12(4).0012

3.2. Basic Principles and Requirements of Civil Engineering Structural Design

3.2.1 Core Principles of Traditional Structural Design

Traditional civil engineering structural design focuses on ensuring engineering quality and service safety, and follows three basic principles:

First, the principle of safety, which ensures that the structure has sufficient strength, stiffness and stability under external loads such as loads, earthquakes and wind forces, so as to meet the safety requirements of engineering use.

Second, the principle of applicability, which requires structural design to conform to the service functions of the project and meet the needs of spatial layout, service comfort and other aspects.

Third, the principle of economy, which optimizes the design scheme, controls project cost and reduces unnecessary cost input on the premise of ensuring safety and applicability.

These three principles constitute the core of traditional structural design, but they do not take low-carbon environmental protection and ecological conservation into account, resulting in prominent high-carbon emission problems in the industry.

3.2.2 Core Principles of Traditional Structural Design

Guided by the low-carbon concept, civil engineering structural design adds three core principles on the basis of retaining the traditional three principles:

First, the principle of low-carbon emission reduction, which aims to reduce life-cycle carbon emissions, optimize schemes from the design source, and reduce building material consumption and energy use.

Second, the principle of sustainability, which prioritizes renewable and recyclable building materials, improves structural durability, extends the service life of projects, and realizes the sustainable utilization of resources.

Third, the principle of ecological friendliness, which takes the surrounding ecological environment into account in structural design, reduces ecological damage caused by construction, and achieves harmonious coexistence between engineering projects and the natural environment.

3.3. Integration Logic of Low-Carbon Concept and Civil Engineering Structural Design

3.3.1 Carbon Emission Components in the Whole Life Cycle of Structural Design

Carbon emissions from civil engineering structures occur throughout their full life cycle, which is mainly divided into five stages:

First, the building material production stage. The production and processing of cement, steel, sand, stone and other materials consume a large amount of energy and generate substantial carbon emissions, accounting for more than 40% of the total carbon emissions of the project.

Second, the design stage. The design scheme directly determines material consumption, structural form and construction method, indirectly affecting carbon emissions in subsequent links, making it the core source for emission reduction.

Third, the construction stage. Carbon emissions are generated by the operation of construction machinery, material transportation, on-site operations and so on. Unreasonable design schemes can increase construction difficulty and material waste, leading to higher carbon emissions.

Fourth, the operation and maintenance stage. Heating, ventilation, lighting and equipment operation during the service life consume energy and produce continuous carbon emissions, which can account for 30% – 50% of the total[13].

Fifth, the demolition and recycling stage. Energy consumption of demolition machinery and disposal of construction waste generate carbon emissions, and low recycling rates further aggravate the environmental burden.

3.3.2 Core Paths for Integrating the Low-Carbon Concept into Structural Design

The core of integrating the low-carbon concept into civil engineering structural design is to achieve emission reduction through design optimization, targeting carbon emission nodes in the whole life cycle from the source and throughout the entire process.

The specific paths are as follows: first, optimize structural selection and layout to reduce the consumption of building materials and lower carbon emissions from material production; second, select low-carbon and environmentally friendly building materials to replace traditional high-carbon materials, reducing carbon emissions at the material source; third, innovate structural systems by adopting efficient structural forms such as prefabricated and modular structures to simplify construction procedures and reduce energy consumption and emissions during the construction phase; fourth, integrate renewable energy design to achieve energy self-sufficiency during operation and reduce operational carbon emissions; fifth, design detachable and recyclable structures to improve the recovery rate of building materials in the demolition phase and reduce carbon emissions from waste.

Through the above paths, the low-carbon concept is integrated into the whole process of structural design, realizing the dual optimization of structural performance and low-carbon emission reduction.

Guided by the low-carbon concept, three core principles are added on the basis of retaining the traditional three principles:

first, the principle of low-carbon emission reduction, which aims to reduce life-cycle carbon emissions, optimize schemes from the design source, and reduce energy use;

second, the principle of sustainability, which prioritizes renewable and recyclable building materials, improves structural durability, extends the service life of projects, and realizes the sustainable utilization of resources;

third, the principle of ecological friendliness, which takes the surrounding ecological environment into account in structural design, reduces ecological damage caused by construction, and achieves harmonious coexistence between engineering projects and the natural environment.

4. APPLICATION PRINCIPLES AND CORE TECHNOLOGIES OF THE LOW-CARBON CONCEPT IN CIVIL ENGINEERING STRUCTURAL DESIGN

4.1. Core Principles of Low-Carbon Structural Design

4.1.1 Principle of Minimizing Life-Cycle Carbon Emissions

This principle serves as the core guiding principle of low-carbon structural design. It requires that structural design is no longer limited to optimizing costs or performance in a single stage, but instead takes the entire life cycle of the project as the accounting period. It comprehensively considers the total carbon emissions throughout the whole process, including building material production, design, construction, operation, and demolition. Through scheme comparison and technical optimization, the design scheme with the lowest total carbon emissions is selected.

At the same time, the safety and economy of the structure must be balanced to avoid sacrificing engineering quality in pursuit of low-carbon goals, so as to achieve a balance between emission reduction and practicality.

4.1.2 Principle of Efficient Resource Utilization and Circular Regeneration

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Based on the concept of circular economy, this principle requires maximizing resource utilization efficiency in structural design and reducing the consumption of non-renewable resources. Recycled materials such as industrial solid waste and construction waste recycled products should be prioritized to replace traditional building materials like cement and sand.

Meanwhile, structural section sizes and reinforcement ratios should be optimized to reduce material waste and avoid over-design.

Long-life, highly durable structures should be designed to extend service life and reduce resource consumption and carbon emissions caused by repeated construction.

4.1.3 Principle of Passive Design Prioritization Over Active Energy Saving

In structural design, passive low-carbon design strategies are adopted first. Through structural layout, form design, orientation optimization and other methods, energy conservation and emission reduction are realized naturally, reducing the use of active equipment such as air conditioning and heating systems.

For example, reasonable design of daylighting and ventilation in building structures reduces lighting and air-conditioning energy consumption during the operation stage. Optimizing the cross-section of bridge structures reduces the amount of steel and concrete used, lowering material carbon emissions at the source, rather than relying solely on energy-saving equipment to achieve emission reduction, thereby lowering project costs and later operation and maintenance energy consumption.

4.2. Key Technology System of Low-Carbon Structural Design

4.2.1 Low-Carbon Building Material Application Technology

Low-carbon building materials serve as the material foundation for realizing low-carbon structural design, mainly including two categories: green environmental-friendly building materials and recycled building materials, and their application technology is a core link of structural design[14]. High-performance low-carbon concrete is the most widely used low-carbon building material. By incorporating industrial solid wastes such as fly ash, slag and silica fume to replace part of the cement, it reduces cement consumption, thereby cutting down carbon emissions generated by cement production[15]. Meanwhile, it improves the durability and strength of concrete and extends the service life of structures.

Low-carbon steel adopts new smelting technologies to reduce energy consumption and carbon emissions in the steelmaking process. Featuring high strength and light weight, it can reduce steel consumption in steel structure design to achieve emission reduction. Recycled aggregate building materials take construction waste and industrial waste as raw materials to process into recycled aggregates, recycled bricks and other products, replacing natural sand and gravel, reducing the exploitation of natural resources and lowering carbon emissions in building material production. In addition, new green building materials such as aerogel thermal insulation materials and low-carbon glass are gradually applied in structural envelope design to enhance the energy-saving performance of structures.

In structural design, it is necessary to reasonably select low-carbon building materials in combination with the project type and load requirements, optimize the mix proportion and application scheme of building materials, and maximize the application proportion of low-carbon building materials on the premise of ensuring structural safety, so as to achieve emission reduction from the material source. Passive low-carbon design methods should be prioritized in structural design. Energy conservation and emission reduction can be naturally realized through structural layout, shape design, orientation optimization and other means, reducing the use of active equipment such as air conditioners and heating equipment. For instance, rational design of daylighting and ventilation of building structures reduces lighting and air-conditioning energy consumption during the operation stage; optimizing the cross-section form

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of bridge structures reduces the consumption of steel and concrete, lowering material carbon emissions from the source, rather than merely relying on energy-saving equipment to achieve emission reduction, thus reducing project costs and later operation and maintenance energy consumption[16].

4.2.2 Energy Efficient Utilization and Low-Carbon Operation and Maintenance Technology

Low-carbon structural design not only focuses on emission reduction in the construction stage, but also pays more attention to efficient energy utilization in the operation stage. It realizes low-carbon operation through the collaborative design of structures and renewable energy. Building Integrated Photovoltaic (BIPV) technology combines solar photovoltaic modules with building structures to replace traditional roof and wall materials[17]. Without occupying additional space, it uses solar energy to generate electricity, meets the power demand of building operation, and reduces indirect carbon emissions caused by power consumption from the power grid. This technology is applicable to public buildings, industrial workshops and high-rise residences.

Ground source heat pump technology is integrated with structural foundations, utilizing shallow underground geothermal resources to realize building heating and cooling. Compared with traditional air conditioning systems, it can reduce operating energy consumption by more than 60% and significantly cut carbon emissions. At the same time, intelligent monitoring technology is introduced into structural design by embedding structural monitoring sensors to monitor the stress, deformation and energy consumption of the structure in real time, optimize the operation and maintenance scheme in a timely manner, reduce unnecessary maintenance and energy waste, extend the service life of the structure, and achieve low-carbon operation and maintenance throughout the full life cycle.

4.2.3 Carbon Reduction and Carbon Sequestration Technologies

The core of carbon reduction technologies is to reduce carbon emissions through design optimization, while carbon sequestration technologies increase carbon dioxide absorption through structural design. The combination of the two achieves low-carbon structural development.

In terms of carbon reduction, structural design avoids over-design and reduces material consumption by optimizing load distribution, member sections and reinforcement ratios. Construction scheme design is optimized to adopt convenient construction techniques, lowering energy consumption of construction machinery and carbon emissions from material transportation. Long-life design is adopted to improve structural durability and reduce carbon emissions caused by repeated construction.

In terms of carbon sequestration, greening design is integrated into building structural design, such as roof greening, vertical greening and overhead floor greening, using plant photosynthesis to absorb carbon dioxide and form building carbon sinks. In the structural design of bridges and municipal engineering, greening spaces are reserved for vegetation planting to enhance the carbon sequestration capacity of projects, offset part of carbon emissions, and thus achieve integration between engineering and ecology.

5. APPLICATION STATUS AND CASE ANALYSIS OF LOW-CARBON CONCEPT IN CIVIL ENGINEERING STRUCTURAL DESIGN

5.1. Current Application Status in China

In recent years, driven by China’s "dual carbon" goals and green building policies, the low-carbon concept has been widely applied in civil engineering structural design with notable effects.

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Policies issued by the Ministry of Housing and Urban-Rural Development and the NDRC require green standards for new buildings, and promote low-carbon technologies, prefabricated buildings and green materials[18]. Technically, low-carbon materials, prefabricated structures and BIM-based low-carbon design have been widely used in buildings, bridges and municipal engineering, with many demonstration projects completed.

Prefabricated structures and low-carbon recycled materials are increasingly popular in construction[19]. Long-span steel-concrete composite bridges have become mainstream, and key projects such as the Hong Kong-Zhuhai-Macao Bridge have balanced emission reduction and safety. Recycled aggregates and modular structures also help reduce resource consumption in municipal engineering.

However, regional development remains unbalanced, with low application in less developed areas. Most projects only use single low-carbon technologies, the full life-cycle concept is not fully implemented, and the overall level still needs improvement.

5.2. Domestic Application Status

In developed countries, low-carbon structural design is well-developed with complete policy, technical and market systems.

Europe mandates nearly zero-energy standards for new buildings, implements full-life carbon accounting, and achieves over 90% application of low-carbon technologies and materials, with German passive houses realizing nearly zero operational carbon emissions.

Japan integrates low-carbon and seismic design, widely uses lightweight steel and seismic isolation structures, and boasts a 95% utilization rate of recycled building materials via a closed-loop construction waste recycling system.

The US applies digital technologies like BIM and AI to achieve accurate carbon emission simulation and optimization for full-life low-carbon design.

Nordic countries focus on ecological design, adopting wood and bamboo structures to enhance carbon sequestration[20].

Their advantages include full-process low-carbon control, strict standards and mature market mechanisms, offering valuable references for China.

5.3. Detailed Analysis of Representative Cases

5.3.1 Case 1: A Prefabricated Low-Carbon Residential Project in Shanghai

This project is a high-rise residential development with a total construction area of about 100,000 square meters, designed to achieve Green Building Two-Star certification and serve as a low-carbon demonstration residence.

In structural design, a prefabricated concrete shear wall system is adopted. Main components including beams, slabs, columns and shear walls are prefabricated in factories and assembled on-site using sleeve grouting technology. Compared with traditional cast-in-place structures, cement consumption is reduced by 25%, steel usage by 15%, construction waste by 80%, and construction period shortened by 40%[21].

In terms of building materials, the main structure uses high-performance low-carbon concrete mixed with fly ash instead of conventional C30 concrete, reducing carbon emissions from cement production. Non-load-bearing walls adopt recycled aggregate concrete blocks, which utilize construction waste recycled materials and reduce the consumption of natural sand and stone.

In addition, the design integrates photovoltaic roofs and passive daylighting and ventilation arrangements, optimizes building orientation and window-wall ratio to lower lighting and air-

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conditioning energy consumption during operation. The project's life-cycle carbon emissions are reduced by more than 35% compared with traditional residences.

Upon completion, the project not only meets residential functions and safety requirements but also achieves remarkable low-carbon and emission-reduction effects, making it a typical demonstration of prefabricated low-carbon residential buildings in China.

5.3.2 Case 2: A Passive Low-Carbon Office Building in Germany

This project is a multi-storey office building, representative of nearly zero-energy low-carbon buildings in Germany.

It adopts a lightweight steel structure and modular system. Low-carbon high-strength steel is used with optimized member sections, reducing steel consumption by 30%.

The building envelope uses aerogel insulation materials and low-carbon glass with excellent thermal performance, eliminating the need for traditional heating systems.

Whole-life carbon accounting is applied throughout the design. Only 100% recycled and green building materials are adopted, with a construction waste recycling rate of 95%[22].

Combined with ground source heat pumps and building-integrated photovoltaics, the building's operational energy is fully supplied by solar and geothermal energy, achieving nearly zero carbon emissions during operation.

In addition, the structure is designed to be demountable, allowing components to be recycled at the end of service life and avoiding resource waste.

Through comprehensive low-carbon design of structural systems, materials and energy, the project reduces life-cycle carbon emissions by 80% compared with conventional office buildings, fully demonstrating the advanced concepts and technical level of full-process low-carbon design abroad.

5.3.3 Case 3: Low-Carbon Structural Design of the Hong Kong-Zhuhai-Macao Bridge

As a world-class long-span cross-sea bridge project, the Hong Kong-Zhuhai-Macao Bridge fully integrates low-carbon concepts into its structural design.

The main bridge adopts a steel-concrete composite structure system, giving full play to the advantages of lightweight high-strength steel and high compressive strength of concrete.

By optimizing the bridge section and reinforcement design, the consumption of steel and concrete is reduced by more than 20%[23].

In terms of building materials, the piers use high-performance marine low-carbon concrete mixed with industrial solid wastes such as slag and fly ash, which improves concrete durability and corrosion resistance, extends the bridge service life to 120 years, and reduces carbon emissions from repeated construction.

During construction, factory prefabrication and on-site hoisting are adopted to cut energy consumption and environmental pollution from offshore construction.

Meanwhile, ecological protection spaces are reserved in the structural design, balancing marine ecology and carbon sequestration.

The project perfectly combines structural safety, long service life and low-carbon emission reduction for long-span bridges, setting a benchmark for low-carbon design in large-scale civil engineering worldwide.

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6. PROBLEMS AND CHALLENGES OF LOW-CARBON CONCEPT IN CIVIL ENGINEERING STRUCTURAL DESIGN

6.1. Problems at the Technical Level

Although most low-carbon building materials have emission reduction advantages, their performance stability needs to be improved. The production technology of high-performance low-carbon materials is immature, difficult to scale up, and output cannot meet market demand, resulting in insufficient supply.

There is a lack of special standards for low-carbon structural design, as well as unified carbon accounting methods and low-carbon performance evaluation indicators. Designers have to rely on experience, making it hard to ensure actual emission reduction effects.

Whole-life carbon emissions in civil engineering involve many complex links and data. Existing accounting models in China suffer from incomplete parameters and inconsistent scopes.

The application of digital technologies such as BIM and digital twins is limited to large-scale projects, with low utilization in small and medium-sized engineering projects.

6.2. Problems at the Economic Level

The initial investment in low-carbon building materials, prefabricated structures, digital design and other technologies is much higher than that of traditional design and construction. High-performance low-carbon materials are priced 20% – 50% higher than conventional materials.

Most emission reduction benefits of low-carbon structural design are reflected in long-term operation and ecological effects, with insignificant short-term economic returns, making it difficult for construction units to achieve quick profits.

Although the state has issued incentive policies for low-carbon buildings and green building materials, implementation in some regions is inadequate, and subsidies and tax incentives have not been fully applied.

6.3. Problems at the Management and Policy Level

China has not yet issued unified national standards for low-carbon structural design and carbon emission evaluation in civil engineering.

Low-carbon assessment criteria vary across regions and projects, leaving no unified basis for low-carbon design and evaluation, making industry management difficult and market behavior hard to regulate.

Civil engineering structural design involves multiple parties: design, construction, material production, operation and maintenance.

At present, these links are independent and lack a collaborative management mechanism.

In some regions, supervision of low-carbon structural design is weak.

Low-carbon indicators are not included in project approval and acceptance, so low-carbon design remains voluntary rather than mandatory.

7. FUTURE TRENDS AND STRATEGIES FOR LOW-CARBON DESIGN IN CIVIL ENGINEERING STRUCTURES

7.1. Future Development Trends

In the future, low-carbon building materials will evolve toward high performance and low cost. Breakthroughs are expected in the research and development of new low-carbon cement,

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recycled high-performance building materials, and ecological building materials, whose performance will reach or even surpass that of traditional building materials, with bottlenecks in large-scale production gradually resolved. Low-carbon structural design will develop in coordination with concepts such as green buildings, ecological engineering, and sponge cities, enabling a high degree of integration between low-carbon engineering and ecological protection. Meanwhile, the carbon trading market for civil engineering will be gradually improved, allowing carbon emission reduction indicators to be traded in a market-oriented manner, thus forming a dual-control system of "standards and the market". Furthermore, universities, research institutions, and enterprises will establish a collaborative innovation mechanism of industry-university-research-application, accelerating the research and development of low-carbon technologies and the transformation of scientific achievements, and promoting the large-scale application of low-carbon technologies in small and medium-sized engineering projects as well as rural areas.

7.2. Countermeasures and Recommendations

Technically, it is necessary to increase R&D investment in low-carbon building materials, low-carbon structural systems and carbon emission accounting technologies, support scientific research institutions and enterprises to jointly tackle key problems, and break through the bottlenecks in the performance and large-scale production of low-carbon building materials. Economically, we should strengthen financial support for low-carbon structural design, and introduce policies such as special subsidies, tax reductions and exemptions, and loan preferences to make up for the initial cost gap of low-carbon design. In terms of management, a collaborative management mechanism covering the entire industrial chain including design, construction, building materials and operation and maintenance should be established to clarify the low-carbon responsibilities of all parties and ensure the implementation of design schemes.

8. CONCLUSION

Based on a systematic study of the application of low-carbon concepts in civil engineering structural design, this paper draws the following conclusions:

First, the integration of low-carbon concepts into civil engineering structural design is an inevitable trend for industrial development and an important measure to achieve China's "dual carbon" goals. Its core lies in optimizing structural schemes at the design source, selecting low-carbon building materials, and innovating structural systems through full-life-cycle carbon emission control, so as to unify emission reduction with structural safety, applicability and economy[24].

Second, a complete technical system covering low-carbon materials, structural system innovation, energy coordination and carbon sink technologies has been formed for low-carbon structural design. Mature practical cases at home and abroad have achieved remarkable results, which can effectively reduce full-life-cycle carbon emissions, resource consumption and environmental pollution of engineering projects.

Third, at present, many problems still exist in China's low-carbon structural design in terms of technology, economy, policy and awareness. Constraints such as insufficient performance of low-carbon building materials, high initial costs and an imperfect standard system have hindered its large-scale application.

Fourth, in the future, low-carbon structural design will develop toward high performance, intelligence and industrialization. Through technological innovation, policy improvement, industrial coordination and talent training, existing problems can be effectively solved, promoting the full low-carbon transformation of the civil engineering industry.

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