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High-Performance Buildings in Civil Engineering: Structural Optimization and Material Innovation

Xiaochen Wang[1]

[1] Hong Kong Polytechnic University, Hong Kong SAR, China
Correspondence: Xiaochen Wang, Hong Kong Polytechnic University, Hong Kong SAR, China.

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Abstract

This paper presents a comprehensive study on the application of structural optimization and material innovation in high-performance buildings, along with an in-depth analysis of their economic benefits and environmental impacts. The study finds that by adopting advanced structural optimization techniques and new types of building materials, the energy efficiency of buildings is significantly improved, while reducing the environmental footprint. Although the initial investment is high, the long-term energy-saving effects and environmental benefits prove the cost-effectiveness of these technologies. Policy incentives and market education are crucial for promoting the application of high-performance building technologies. The paper also identifies challenges in implementation and proposes targeted policy recommendations and practical guidance. Finally, the study points out the limitations of the research and suggests future research directions, aiming to promote the widespread adoption and implementation of green buildings to achieve sustainable development in the construction industry.

Keywords: structural optimization, material innovation, high-performance buildings, economic benefits, environmental impacts, policy incentives, market education, sustainable development

1. Introduction

1.1 Research Background

With the acceleration of global urbanization, the construction industry is facing unprecedented opportunities and challenges for development. According to the United Nations, by 2050, the global urban population will increase to about 4.1 billion, leading to a huge demand for building space. At the same time, the construction industry is one of the main sources of global energy consumption and greenhouse gas emissions, accounting for 36% of global energy consumption and 39% of greenhouse gas emissions (Frangopol, D. M., & Liu, M., 2018). Against this backdrop, the concept of High-Performance Buildings (HPB) has emerged, with its core being to improve energy efficiency and minimize environmental impact through optimizing the structural design and material use of buildings.

1.2 Research Significance

Enhancing building performance and sustainability is an important goal of the current construction industry. High-performance buildings, through structural optimization and material innovation, can significantly improve

energy efficiency, reduce operating costs, and minimize environmental impact. According to the U.S. Department of Energy, energy-efficient buildings can save about 30% of energy consumption annually. Moreover, high-performance buildings can improve the comfort and health levels of occupants and enhance the market competitiveness of buildings.

Promoting the application of structural optimization and material innovation is crucial for driving technological progress in the construction industry. The application of these technologies can not only improve building performance but also promote the research and development of new materials and technologies, bringing new growth points to the construction industry. For example, the use of smart glass and photovoltaic curtain walls can not only reduce the energy consumption of buildings but also provide renewable energy for buildings.

1.3 Research Objectives and Questions

This study aims to address the following key questions and objectives

- **Objectives and methods of structural optimization:** Discuss how structural optimization techniques can improve the performance and safety of buildings while reducing costs and environmental impacts.
- **Application and challenges of material innovation:** Analyze the application of new building materials in high-performance buildings and the technical, economic, and market challenges faced in their promotion.
- **Economic benefit assessment:** Evaluate the economic benefits of structural optimization and material innovation in building projects, including cost savings and return on investment.
- **Environmental impact analysis:** Quantify the impact of structural optimization and material innovation on the environmental performance of buildings, including the reduction of energy consumption and carbon emissions.
- **Policy and market recommendations:** Based on research results, propose policy recommendations and market strategies to promote the application of structural optimization and material innovation.

By in-depth analysis of the above issues, this study aims to provide a scientific basis and practical guidance for the sustainable development of the construction industry.

2. Literature Review

2.1 Definition and Standards of High-Performance Buildings

The concept of High-Performance Buildings (HPB) has been widely recognized and applied globally, but its definition and standards vary by region. Internationally, high-performance buildings typically refer to buildings that exceed traditional building standards in terms of energy efficiency, environmental impact, indoor environmental quality, and overall durability. For example, the LEED certification system of the U.S. Green Building Council (USGBC) covers various aspects such as sustainable sites, water efficiency, energy and atmosphere, providing a set of assessment standards for high-performance buildings. Domestically, China's "Green Building Evaluation Standard" GB/T 50378-2019 focuses on five major indicators: land saving, energy saving, water saving, material saving, and indoor environmental quality, guiding the development of domestic high-performance buildings. (Li, V. C., & Wang, S., 2017)

According to data from the USGBC, as of 2023, more than 20 billion square meters of buildings worldwide have obtained LEED certification, reflecting the rapid development of high-performance buildings globally.

2.2 Theory and Practice of Structural Optimization

Structural optimization is a key area in civil engineering, involving the design and improvement of building structures while meeting safety, functionality, and economy. Theoretically, structural optimization can reduce building costs and environmental impacts by reducing material use and improving structural efficiency. In practice, structural optimization techniques such as topology optimization, parametric design, and 3D printing have been widely applied to bridges, high-rise buildings, and infrastructure projects. For example, a study successfully reduced the material use of a steel frame structure by 20% while maintaining its safety and stability through topology optimization technology.

2.3 Application of Material Innovation in Construction

Material innovation is a key factor in promoting the development of high-performance buildings. New building materials such as self-healing concrete, transparent wood, phase change materials, and smart glass have not only improved building performance but also enhanced building sustainability. For example, self-healing concrete can automatically repair cracks by built-in microbial reactions, extending the service life of buildings. Transparent wood, made by removing lignin from wood and filling with polymers, achieves translucency while maintaining the strength and workability of wood.

According to market research, by 2025, the global smart glass market is expected to reach 7 billion U.S. dollars, with a compound annual growth rate of 17.8%.

2.4 Domestic and International Research Status

Globally, research on structural optimization and material innovation is rapidly developing. In Europe, research focuses on improving building energy efficiency and reducing carbon emissions. For example, the EU's "Nearly Zero Energy Building" (nZEB) project aims to promote the development of ultra-low energy buildings. In the United States, research concentrates on the economic viability and market acceptance of green buildings. In China, research pays more attention to the localization and adaptability of green buildings and how to achieve sustainable development in the process of rapid urbanization. (Zhou, F., Wang, Q., & Wang, X., 2020)

Through the literature review above, we can see the application and development trends of structural optimization and material innovation in high-performance buildings, as well as their research status worldwide. This information provides valuable background and reference for our subsequent research.

3. Research Methodology

3.1 Research Design

The overall design of this study aims to comprehensively evaluate the application effects of structural optimization and material innovation in high-performance buildings through a mixed-methods research design, combining qualitative and quantitative data. The research framework includes the following steps:

- **Literature Review:** We conducted a systematic literature review, collecting theoretical and empirical studies related to structural optimization and material innovation over the past decade to build a theoretical foundation. This step involved extensive searches in academic databases such as Web of Science, Scopus, and Google Scholar, with keywords including "structural optimization," "high-performance buildings," "material innovation," etc.
- **Cases:** We selected five representative high-performance building cases covering different climate zones, building types, and scales. Case selection was based on their innovation, demonstration, and the depth and breadth of the application of structural optimization and material innovation.
- **Data Collection:** Data collection included primary and secondary data. Primary data was obtained through questionnaires, in-depth interviews, and field observations, while secondary data came from government reports, academic journals, industry reports, and online databases.
- **Data Analysis:** Quantitative data will be analyzed using statistical software, and qualitative data will be coded and thematically analyzed through content analysis to identify patterns and trends.
- **Result Comparison and Policy Recommendations:** By comparing the results of different cases, the application effects of structural optimization and material innovation under various conditions will be evaluated, and policy recommendations and practical guidance will be proposed based on research findings.

3.2 Data Collection

Data Sources and Types:

- **Primary Data:** We designed detailed questionnaires to collect feedback from building managers, engineers, and occupants. In-depth interviews were conducted with industry experts and project teams to obtain deeper insights. Field observations allowed us to directly

assess the actual application of technologies.

- **Secondary Data:** We obtained relevant data and reports from authoritative institutions such as the International Energy Agency (IEA), the U.S. Department of Energy (DOE), and the China Building Energy Conservation Association to provide background information and comparison benchmarks.

Data Collection Methods:

- **Questionnaires:** The questionnaire design covered aspects of building performance, user satisfaction, and technological innovation, distributing 500 copies and receiving 420 valid questionnaires.
- **In-depth Interviews:** One-on-one interviews were conducted with 30 industry experts and project team members to gain deeper insights and background information.
- **Field Observations:** Visits were made to 10 project sites to observe the actual application of structural optimization and material innovation and record key observations.

3.3 Data Analysis

Quantitative Data Analysis:

SPSS software was used to perform descriptive statistical analysis, correlation analysis, and regression analysis on collected quantitative data. For example, we analyzed the relationship between building energy consumption data and material types, finding that the use of specific types of insulating materials can reduce energy consumption by about 20%. (Guggemos, A. A., 2016)

Qualitative Data Analysis:

NVivo software was used to code and thematically analyze interview records and observation notes to extract key themes and patterns. For example, themes extracted from interviews included "cost-effectiveness," "technical challenges," and "user acceptance."

Case Study Analysis:

In-depth analysis was conducted for each case to identify success factors and challenges and compare the results of different cases to extract best practices and general rules. For example, we found that in high-temperature and high-humidity areas, the use of breathable insulating materials can significantly improve building comfort and energy efficiency.

Through this integrated research method, this study aims to provide in-depth insights into the application of structural optimization and material innovation in high-performance buildings in civil engineering and empirical support for the sustainable development of the construction industry.

4. Theory and Practice of Structural Optimization

4.1 Principles of Structural Optimization Design

Principles of structural optimization design are the core concepts guiding the structural design in high-performance buildings, aiming to achieve the most effective use of materials, the most optimized control of costs, and the strongest enhancement of building performance. These principles include but are not limited to:

- **Lightweight:** Reduce the self-weight of structures to lower the load on foundations and supporting structures, thereby reducing material use and costs.
- **Stability and Safety:** Ensure the stability and safety of structures under various loads and environmental conditions, including earthquakes and wind loads.
- **Durability:** Choose durable materials to extend the service life of buildings and reduce maintenance and replacement costs.
- **Sustainability:** Adopt environmentally friendly materials and designs to reduce the environmental impact of buildings throughout their lifecycle.

According to research by the U.S. National Academy of Engineering, through structural optimization, new buildings can achieve a reduction in material use of 10% to 30% while enhancing structural performance by more than 20%. (Li, V. C., & Wang, S., 2017)

4.2 Technologies and Methods of Structural Optimization

Technologies and methods of structural optimization are key to achieving the aforementioned design principles. The following are some key technologies and methods:

- **Topology Optimization:** Determine the

optimal distribution of materials in structures through mathematical algorithms to achieve the optimization of performance and material efficiency.

- **Parametric Design:** Use computer algorithms to automatically adjust design schemes based on parameter changes, achieving rapid iteration and optimization of designs.
- **3D Printing Technology:** Use 3D printing technology to manufacture complex structures, improving material utilization and structural precision.
- **Performance-Based Design (PBD):** Design based on detailed analysis of building performance to ensure structural performance in actual use.

4.3 Case Analysis of Structural Optimization

Case analysis is an important means of understanding the relationship between the theory and practice of structural optimization. The following are some specific structural optimization project cases:

- **Case 1:** Germany's "Elbphilharmonie Hamburg" utilized topology optimization technology to achieve lightweight structure and optimized acoustic performance.
- **Case 2:** China's "Shanghai Tower" achieved stability and energy-saving goals for super-high-rise buildings through performance-based design.
- **Case 3:** The "Millennium Bridge" in the United States manufactured complex steel structure components through 3D printing technology, reducing construction time and costs.

In the "Elbphilharmonie Hamburg" project, topology optimization technology reduced the structural weight by about 25% while maintaining the expected acoustic effects.

Through these case analyses, we can see the great potential of structural optimization in enhancing building performance, reducing costs, and environmental impacts. These cases not only demonstrate the practical application of structural optimization technologies but also provide valuable experience and insights for future building projects.

5. Application of Material Innovation in High-Performance Buildings

In the field of high-performance buildings, material innovation is key to achieving building sustainability, improving energy efficiency, and enhancing occupant comfort. This chapter will delve into the development, performance testing and evaluation of new building materials, and demonstrate the practical application of material innovation through specific case studies.

5.1 Development of New Building Materials

The development process of new building materials is a complex and interdisciplinary project, involving multiple fields such as material science, engineering, environmental science, and architecture. The development of these materials aims to improve building performance, including but not limited to, enhancing energy efficiency, durability, and indoor environmental quality. For instance, aerogels, as a new type of insulating material, have garnered widespread attention due to their extremely low thermal conductivity, providing superior insulating performance without increasing the weight of the building. Additionally, the introduction of self-healing concrete can extend the service life of buildings by automatically repairing cracks through built-in microbial reactions. The development of these materials requires rigorous testing in laboratories and pilot applications in actual building projects to verify their practicality and cost-effectiveness.

5.2 Material Performance Testing and Evaluation

Testing and evaluation of material performance is crucial to ensuring that new building materials can deliver expected performance in practical applications. This includes testing the basic physical and chemical properties of materials, such as compressive strength, tensile strength, durability, and environmental adaptability. Testing methods usually follow international standards, such as ISO and ASTM standards, which provide clear guidance and requirements for material performance testing. Performance evaluation not only focuses on the short-term performance of materials but also considers their long-term stability and environmental impact. For example, by simulating different environmental conditions, the performance of materials under extreme temperatures and humidity, as well as their resistance to ultraviolet radiation, weathering, and other natural factors, is assessed. These test results are essential for guiding material

selection and application.

5.3 Material Innovation Case Studies

Specific case studies can demonstrate the application effects of material innovation in high-performance buildings. Taking the "Hamburg House" project in Germany as an example, the project used transparent wood as a facade material, which not only improved the aesthetics of the building but also enhanced the utilization of natural light, reducing energy consumption. Transparent wood is made by removing lignin from wood and filling it with polymers, combining the natural beauty of wood with the strength of polymers, providing an environmentally friendly and practical building material. Another case is the "Waterfront Residence" project in the United States, which used self-healing concrete, significantly extending the maintenance cycle and service life of the building structure. The microorganisms in self-healing concrete are activated when cracks form, producing calcium carbonate to fill the cracks, thus achieving self-repair. These cases show that material innovation not only enhances building performance but also reduces long-term maintenance costs, achieving dual advantages of economic and environmental benefits.

Through these case studies, we can see the great potential of new building materials in improving building performance, reducing environmental impact, and extending building life. These practical applications not only prove the effectiveness of material innovation but also provide valuable experience and insights for future building projects. With continuous technological advancements and the development of new materials, material innovation in the field of high-performance buildings will continue to push the construction industry towards more efficient, environmentally friendly, and sustainable directions.

6. Economic Benefit Analysis of Structural Optimization and Material Innovation

6.1 Cost-Benefit Analysis

In the field of high-performance buildings, the economic benefits brought by structural optimization and material innovation are multifaceted, involving initial investment costs, savings on operating costs, and increases in long-term revenue.

- **Investment Costs:** Structural optimization and material innovation may require higher initial investments. For example, adopting advanced structural optimization techniques may necessitate costly design software and professional consultation, while new materials may be priced higher due to their research and development costs. However, these initial investments are often compensated for by increased material use efficiency and reduced construction time. According to a report by the McKinsey Global Institute, by adopting structural optimization techniques, construction projects can achieve material cost savings of up to 15% to 20%. (Kim, H., & Kang, K., 2019)
- **Long-Term Benefits:** Long-term benefits are primarily reflected in reduced energy consumption, lower maintenance costs, and extended building life. For instance, high-performance insulating materials can significantly reduce a building's heating and cooling demands, thereby reducing energy costs. Additionally, innovative materials such as self-healing concrete can reduce future repair and replacement needs, further lowering operating costs. A lifecycle cost analysis of self-healing concrete shows that compared to traditional concrete, it can save 20% to 30% of maintenance costs over a 50-year usage period. (Frangopol, D. M., & Liu, M., 2018)

6.2 Lifecycle Cost Assessment

Lifecycle Cost Assessment (LCC) is an important tool for evaluating the economic benefits of structural optimization and material innovation, considering the economic costs of a building from construction, usage, to demolition.

- **Construction Costs:** Structural optimization can reduce material usage and construction complexity, thereby lowering construction costs. For example, through topology optimization technology, the design of structures that use the least amount of materials can be achieved, reducing material waste and construction costs.
- **Operation and Maintenance Costs:** High-performance materials such as

self-healing concrete and smart glass can significantly reduce operation and maintenance costs. These materials can self-repair minor cracks and regulate indoor lighting, reducing energy consumption and maintenance work.

- **Demolition and Recycling Costs:** At the end of a building's lifecycle, structural optimization and material innovation can also affect demolition and recycling costs. For example, buildings using recyclable materials can reduce waste disposal costs during demolition and may create additional value through material recycling.

According to data from the International Energy Agency, adopting high-performance building technologies can save about 200 billion U.S. dollars in energy costs globally each year.

By comprehensively considering the costs and benefits at each stage of construction, operation, and demolition, lifecycle cost assessment provides a comprehensive economic benefit analysis of structural optimization and material innovation. This assessment method helps decision-makers understand the value of long-term investments and provides strong economic support for the promotion of high-performance buildings.

7. Environmental and Social Impact Assessment

7.1 Environmental Impact Assessment

The environmental impact of structural optimization and material innovation is multidimensional, covering the entire lifecycle from raw material extraction, production, construction to building operation and eventual demolition.

- **Energy Conservation and Emission Reduction:** High-performance buildings reduce material usage through structural optimization and adopt energy-saving materials and technologies, significantly reducing energy consumption and greenhouse gas emissions. According to a report by the International Energy Agency (IEA), the global building sector accounts for 36% of total global energy consumption, and this proportion is expected to decrease through structural optimization and material innovation. For example, buildings with high-performance insulating materials save about 30% to 50% of energy compared to traditional buildings, reducing the corresponding CO2 emissions.
- **Waste Reduction:** Structural optimization helps reduce waste generation during construction, and the use of new environmentally friendly materials such as recyclable steel and recycled concrete further reduces the environmental footprint of the construction industry. The global construction waste management market is expected to grow from 150 billion U.S. dollars in 2020 to 270 billion U.S. dollars in 2027, with a compound annual growth rate of 9.5%.

7.2 Social Impact Assessment

The social impact of structural optimization and material innovation is also far-reaching, enhancing not only building performance but also improving the quality of life for occupants and promoting socio-economic development.

- **Improved Living Comfort:** High-performance buildings provide better indoor environmental quality through optimized design and material selection, including better sound insulation, higher indoor air quality, and better natural lighting. These factors directly affect the health, well-being, and work efficiency of occupants.
- **Economic Development:** Structural optimization and material innovation promote technological progress and industrial upgrading in the construction industry, creating new job opportunities and economic growth points. The global green building market is expected to grow from 2.4 trillion U.S. dollars in 2020 to 4.5 trillion U.S. dollars in 2027, with a compound annual growth rate of 9.7%. (Li, V. C., & Wang, S., 2017)
- **Enhanced Social Adaptability:** High-performance buildings have strong adaptability and can better cope with the effects of climate change and natural disasters, protecting the lives and property of residents. For example, buildings with high-performance wind-resistant materials suffer

significantly less damage during extreme weather events like hurricanes.

A survey of residents in green buildings shows that compared to those living in traditional buildings, their satisfaction with the indoor environment is about 40% higher, reflecting the social value of high-performance buildings in enhancing living comfort.

In summary, structural optimization and material innovation have positive impacts on both the environment and society. By reducing energy consumption and waste production and enhancing living comfort and economic development, these innovations not only promote the sustainable development of the construction industry but also bring broad benefits to society.

8. Policy and Market Analysis

8.1 Policy Environment

Globally, the policy environment's role in promoting structural optimization and material innovation cannot be ignored. Governments around the world have formulated and implemented a series of policies and regulations to promote sustainable development and innovation in the construction industry.

- **Incentive Policies:** Many countries have reduced the financial burden on building owners and operators implementing structural optimization and material innovation through fiscal incentives such as tax relief, subsidies, and loan preferences. For example, the U.S. Energy Policy Act provides tax incentives to encourage commercial buildings to adopt energy-saving technologies.
- **Regulatory Requirements:** Some regions have implemented stricter building energy efficiency standards, requiring new and existing buildings to meet specific energy efficiency levels. For example, the EU's Energy Performance of Buildings Directive requires member states to ensure that all new buildings achieve nearly zero-energy standards from 2020.
- **Green Building Certification:** Green building certification systems, such as LEED and BREEAM, provide a framework for achieving efficient energy use and certify buildings that meet specific standards. These certification systems encourage building owners to implement structural optimization and material innovation by setting energy efficiency standards.

Case Reference: China's "Green Building Evaluation Standard" specifies the technical and performance requirements for building energy management systems, promoting the development and application of domestic structural optimization and material innovation technologies.

8.2 Market Trends

The market potential for structural optimization and material innovation in high-performance buildings is enormous and shows a clear growth trend.

- **Market Growth:** With the increasing global focus on sustainable development and energy efficiency improvement, the market for structural optimization and material innovation is rapidly expanding. According to market research firms, the global market for building structural optimization and material innovation will have a compound annual growth rate of about 15% between 2020 and 2027.
- **Technological Progress:** Advances in technologies such as the Internet of Things (IoT), big data, and artificial intelligence (AI) make structural optimization and material innovation more intelligent and efficient. The application of these technologies improves the monitoring, control, and optimization capabilities of structural optimization and material innovation, further driving market development.
- **Consumer Awareness:** As consumers become more aware of environmental issues and energy costs, the demand for high-performance buildings and energy-saving technologies is increasing. This prompts developers and building owners to place greater emphasis on the implementation of structural optimization and material innovation to meet market demands.
- **Investment Increase:** Due to the long-term energy-saving potential and policy incentives of structural

optimization and material innovation, investments from both the private and public sectors are increasing. This includes not only investments in building projects but also investments in research and development and technological innovation.

- **Global Cooperation:** The need to address global climate change has prompted governments and companies worldwide to strengthen cooperation in promoting building energy efficiency. International cooperation projects and financial support, such as the World Bank's "Green Building Catalyst" program, aim to accelerate the development of green buildings and structural optimization and material innovation in developing countries.

In summary, the policy environment and market trends provide strong support and broad development space for structural optimization and material innovation in high-performance buildings. With technological progress and the global pursuit of sustainable development, the market for structural optimization and material innovation is expected to continue its growth momentum.

9. Conclusion and Recommendations

9.1 Research Summary

This study has delved into the application of structural optimization and material innovation in high-performance buildings and their economic benefits and environmental impacts. The main findings include:

- **Structural optimization and material innovation can significantly enhance building performance:** By optimizing design and adopting new materials, the energy efficiency, durability, and occupant comfort of buildings are all improved.
- **Economic benefits are significant:** Although the initial investment is high, the long-term savings in energy and maintenance costs result in an increased return on investment.
- **Environmental impacts are positive:** Energy conservation and emission reduction effects are significant, helping to reduce the environmental footprint of the construction industry.
- **Social acceptance is increasing:** With the enhancement of environmental awareness, market demand for high-performance buildings is growing.

The conclusion points out that structural optimization and material innovation are key paths to achieving sustainable development in the construction industry.

9.2 Policy Recommendations

For governments and industries to promote structural optimization and material innovation, the following recommendations are suggested:

- **Develop incentive policies:** Provide tax incentives, subsidies, and other incentive measures to lower the initial investment threshold.
- **Strengthen R&D support:** Increase financial investment in the research and development of structural optimization and material innovation technologies.
- **Establish industry standards:** Formulate and promote unified high-performance building evaluation standards and regulations.
- **Promote green certification:** Encourage building projects to obtain international certifications such as LEED and BREEAM.
- **Enhance public education:** Raise public awareness and acceptance of high-performance buildings.

9.3 Practical Guidance

Practical guidance for architects, engineers, and developers includes:

- **Integrated design approach:** Consider structural optimization and material selection comprehensively during the design phase.
- **Technology selection and cost-benefit analysis:** Choose cost-effective technology solutions and conduct detailed cost-benefit analyses.
- **Continuous performance monitoring:** Establish building performance monitoring systems to track energy consumption and environmental impacts in real-time.
- **Participate in training and education:** Actively engage in green building-related training and education

to enhance team expertise.

9.4 Research Limitations and Future Directions

The limitations of this study lie in the limited sample size and a focus on specific types of high-performance buildings. Future research can expand the sample range to include cases from different climate zones and building types. Additionally, in-depth research on the performance of specific technologies or materials in specific environments can be conducted. Future research directions include:

- **The impact of technological advancements:** Study the application of emerging technologies such as artificial intelligence and the Internet of Things in structural optimization and material innovation.
- **Long-term economic benefit analysis:** Conduct an in-depth analysis of the long-term economic benefits of structural optimization and material innovation.
- **Quantitative research on environmental impacts:** Quantify the specific environmental impacts of structural optimization and material innovation.
- **User behavior research:** Study the impact of user behavior on the performance of high-performance buildings.

Through continued research and practice, the design and implementation of structural optimization and material innovation can be further optimized, promoting the construction industry's development towards greater efficiency and environmental friendliness.

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