Journal of World Architecture

BIO-BYWORD SCIENTIFIC PUBLISHING PTY LTD
(619 649 400)
Level 10
50 Clarence Street
SYDNEY NSW 2000

Complimentary Copy

ISSN (ONLINE): 2208-3499
ISSN (PRINT): 2208-3480

Journal of World Architecture

Focus and Scope

The *Journal of World Architecture* is a peer-reviewed international journal, which offers an avenue for researchers and practitioners to present the latest progress associated with architecture, occupants and related policies. It aims to encourage academic exchange and enhancing professional development in this field.

Topics covered but not limited to:

- Architecture theories and practices of design, technology and construction;
- Impacts of architecture on society, economy and environment;
- Analysis of occupants physically and psychologically and the application of new technologies, materials to meet their needs;
- Formulation of public policy as well as organisational structures and networks.

About Publisher

Bio-Byword Scientific Publishing is a fast-growing, peer-reviewed and open access journal publisher, which is located in Sydney, Australia. As a dependable and credible corporation, it promotes and serves a broad range of subject areas for the benefit of humanity. By informing and educating a global community of scholars, practitioners, researchers and students, it endeavours to be the world's leading independent academic and professional publisher. To realize it, it keeps creative and innovative to meet the range of the authors' needs and publish the best of their work.

By cooperating with University of Sydney, University of New South Wales and other world-famous universities, Bio-Byword Scientific Publishing has established a huge publishing system based on hundreds of academic programs, and with a variety of journals in the subjects of medicine, construction, education and electronics.

Publisher Headquarter

BIO-BYWORD SCIENTIFIC PUBLISHING PTY LTD
Level 10
50 Clarence Street
Sydney NSW 2000
Website: www.bbwpublisher.com
Email: info@bbwpublisher.com

2025, Volume 9, Issue 5

Table of Contents

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Critical Regionalism for Ingratiation: China's Foreign-Aided Stadiums After 2000

Wei Chang[1,2]*, Yifan Gao[1], Xiaofeng Guo[3], Guang Yang[1], Charlie Xue[4]

[1]School of Fine Arts, Tangshan Normal University, Tangshan, China
[2]School of Civil Engineering and Mechanics, Yanshan University, Hebei, China
[3]China Railway Beijing Group Co., Ltd., Beijing, China
[4]Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China

**Author to whom correspondence should be addressed.*

Abstract: Stadiums have been one of China's most well-known and influential foreign aid projects that attract considerable attention. After 2000, a series of reforms in China's foreign aid generated significant influences on the designs of China's foreign-aided buildings, especially on large constructions such as stadiums. The authors aim to explore the development of China's foreign-aided stadiums after 2000 and analyze the influential aspects on the design processes. Critical regionalism for ingratiation is identified as the main architectural feature. The study is conducted through a detailed analysis of the foreign aid mechanism, case projects, first-hand materials, and interviews with Chinese architects involved. The authors consider these stadiums to represent a unique critical regionalism with cultural and climate elements embedded. It can be regarded as a considerable supplement to the current scholarship on Chinese contemporary architecture and Chinese sports buildings.

Keywords: China's foreign-aided stadium; Critical regionalism; After 2000

Online publication: October 21, 2025

1. Introduction

Since the 1950s, China has exported over 100 stadiums to the developing world, as one significant category of its construction aid, which attracts much attention from the academic world [1–4]. However, most studies discuss the diplomatic influence referred to as China's "stadium diplomacy" [5–9], rather than their architectural development [10–16], especially for the contemporary period. Although China has experienced the reform of market economy in construction since the 1980s, China's foreign-aided projects were still under the management of planned economy models before 2000 [14]. After 2000, more reforms were finally introduced into China's foreign-aided projects. China's foreign-aided stadiums benefit from such reforms and start to have new characteristics. Under such new circumstances, what are the main influential factors on these stadium designs, and what are the main attributes of these architectural outcomes that show the current development of Chinese architectural design and its attitude and working modes in the face of overseas projects under the special diplomatic background? These constitute the main aims of this study.

2. China's aid mechanism of the new era: Market reform and bilateral mechanism

In the new century, China rapidly expanded its overseas aid activities to become one of the main non-Western donors [17] and began to provide more aid to the countries along the BRI (Belt and Road Initiative) [18,19]. After decades' economic reform, marketization was finally introduced into China's foreign-aided construction projects after 2000, 20 years behind China's domestic circumstances [20]. More forms of economic aid were implemented besides grants, such as interest-free loans and concessional loans after 2000 [21]. Larger and more diversified financial support for construction projects contributes to the profound improvement of China's foreign-aided stadiums of the new era. Another effect generated by the new mechanism is that the recipient countries participate more in the process, especially for large, significant public buildings such as stadiums [11]. For the recent significant China's foreign-aided stadiums, the winning schemes in the bid are finally selected by the representatives of recipient countries from the alternative schemes chosen by China's domestic experts. In the later processes of reviews and constructions, the recipient countries are also gaining more involvement. All these make the mechanism towards bilateral.

3. China's foreign-aided stadiums: Adjustment and adaptation through cooperation and competition

After 2000, China increased its number of foreign-aided stadiums. Over 60 stadiums were exported to other countries by China, with about three-fourths being outdoor stadiums and the rest being indoor. The number of stadiums experienced explosive growth and the geographic distribution varies in the fourth continents (Africa, Asia, Latin Africa, and Oceania) of the first decades [14] but returned to focus the Africa and Asia after the BRI was proposed. Generally, 60% (36 stadiums) are located in Africa, while over 10% (7 stadiums) are in Asia (**Figure 1**). Since China's aid diplomacy transformed from grants to cooperation with various financial support modes, the scales and standards of these stadiums have also increased significantly compared with the previous periods.

3.1. Transition and adaptation under new circumstances

The new bid system in China's foreign-aided constructions provided chances for more Chinese design institutes to be involved in the first decade of the new century, including private firms (e.g., CCDI). Architectural designs of these stadiums benefited from various participants with diversified schemes, and the working mode tended to be parallel with that of commercial projects. Another transition lies in the working mode of architects that turned out to be more flexible, with multi-cooperation, especially with overseas companies, such as the My Dinh National Stadium in Hanoi and the Mahinda Rajapaksa International Cricket Stadium in Jamaica. After the Beijing 2008 Summer Olympics Games, China has been conducting intensive construction of sports venues consistent with the high international standards, not only in its capital but also in other major cities, which in turn has improved the design and construction level of stadiums constructed in the aid program. Chinese architects and design institutes got more practice and, coincidentally, returned to the court of designing foreign-aided stadiums independently after the 2010s.

Under such transitions, China's foreign-aided stadiums in the new era tend to be more diversified with higher standards, larger scales, and more powerful influence. Some of China's best foreign-aided stadiums were

Figure 1. Regional distribution of China's foreign-aided stadiums after 2000

designed and constructed. Over ten stadiums used full-coverage roofs, and many had tried the “skin” language in architectural expression, which required higher cost and more complex structures and materials. Recently, many recipient countries expect these aid buildings to be the symbol of the modern level of the city/country and to be qualified for the application of significant international sports events and other national events. The bidding mechanism forced Chinese architects to satisfy the recipient country’s preference, especially when it became the final decision-maker during the reform. Chinese architects started to introduce more regional design approaches, with attention to the local culture and climate, in their understanding in exploration of modern design languages. Such regional concerns in the architectural design of stadiums tend to break the economic limitations and conservative routines. More large-scale, multi-dimensional, and high-profile expressions of regional aspects were integrated in the outdoor stadiums. And these efforts gradually transformed from designs with the understanding of Chinese own understandings, to more ingratiating for the recipient countries.

3.2. Case studies

Three cases were selected for a comprehensive understanding. The national stadium of Tanzania was designed in the early years of the 2000s and was also the first case in which Chinese architects cooperated with a foreign design company. The design work of China’s foreign-aided stadium in the Ivory Coast lasted from the late 2000s to the early 2010s. The last stadium case in Cambodia was designed in recent years as China’s largest and most costly aid stadium ever since. These cases can illustrate the most recent development of architectural features of China’s foreign-aided stadiums after 2000.

3.2.1. Adapting standards and techniques: National Stadium of Tanzania

As it established diplomatic relations with China in 1964, Tanzania received a large amount of construction aid from China, such as factories and collieries, among which was China’s first large-scale aid project, the Tanzania-Zambia railway of 1,860 km long in 1975. For this newly independent country, sports played a crucial role in its nation-building process, and the stadium became a significant venue where national events were held, such as the National Liberation Day.

Designed by two South African companies, the initial scheme followed South African standards and adopted the usage habits of the Tanzanian locals. However, detailed and technical designs (including structures and materials) by BIAD needed to use the Chinese standard, for the construction to be led by BCEG in cooperation with Tanzanian contractors. This required Chinese architects to adapt Chinese standards into the local ones and which were used in the initial design. Although it was not the original creation completed by Chinese architects, how Chinese architects tried to adapt Chinese standards to the local designs through their developing designs is interesting and worthy of discussion.

Located in Dar es Salaam next to Uhuru Stadium, Tanzania’s previous national stadium, the new national stadium, also known as Benjamin Mkapa Stadium, has a 60,000-seat capacity and 69,050 m^2 gross floor area. With the considerations of Tanzania’s love for football games and the low frequency of track and field competitions, the shape of the stands was designed to hold two straight east-west edges and two semicircles to minimize the horizontal distance between the audience and the site for football games. This is quite different from the four-circle-center shape as commonly used in China’s domestic. The general layouts of the floors, the roof forms, and the surrounding facades also followed the shape of stands [22]. As over 10% of the local population was disabled, the conceptual design placed two large cross slopes on the north and south sides following the semicircle shape, and one centralized slope at the main entrance to connect the ground floor and first floor. The idea was well conveyed in the in-depth design by Chinese architects and was even improved to better serve the capacity of traffic to the stadium by replacing the single slope of the main entrance with two separated ones alongside (**Figure 2**). The adjustment was also in coincidence with the site designs developed by the Chinese institute, with symmetric axial squares and parking areas. Besides, more quantities of seats for disabled people were arranged in this overseas stadium, which was of a higher standard than China's domestic barrier-free design standard [14].

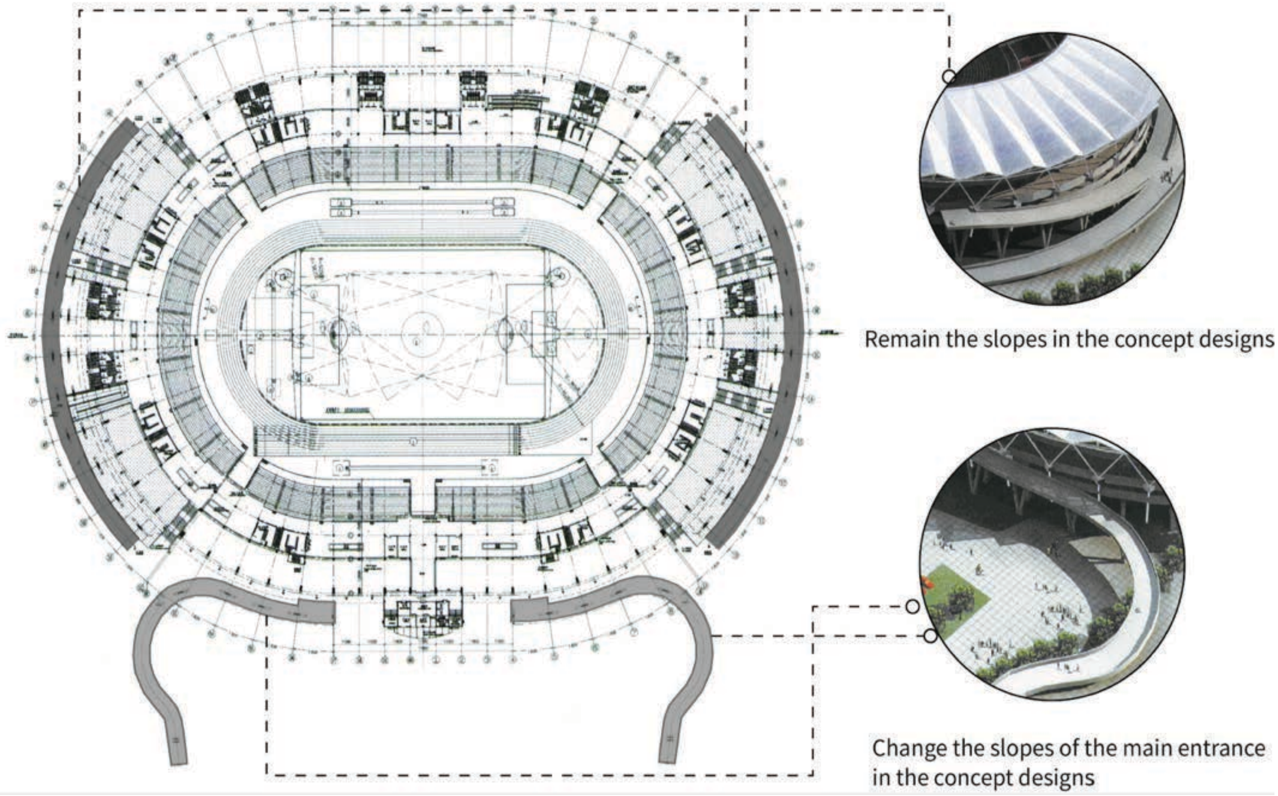


Figure 2. Improvement of the designs by Chinese architects in the China-aided national stadium of Tanzania (Source: drawn by the authors based on reference [22])

In addition, standards were not the only challenges that faced Chinese technicians. To portray a modernized stadium with advanced technologies, WAS Architects' initial designs used the membrane roof to fully cover the two-layer stands, together with the mainstream development of stadiums worldwide. To achieve the modern, international, and high-tech image, more advanced structures and technologies were utilized in the in-depth design by BIAD. The spatial pipe truss (for the main perpendicular and roof structure) and the cable-membrane tension structure were used in the stadium. Chinese architects introduced more V-shaped supporting columns than indicated in their initial designs. However, the repeating curved membrane roof was replaced by the folding triangular plane-shape membrane roof with V-shape section, which simplified the membrane structure and material requirements. Nevertheless, the structural teams of BIAD still tried hard on the structural designs [23,24], as the membrane structure was not commonly used in Chinese domestic stadiums at the beginning of the new century. The new structure reduced the weight to generate a more light-hearted appearance. Also, the roof was constructed with an advanced ETFE material that had heat-resistant abilities (with solar reflectance above 70%). To improve the rainfall shortage in Dar es Salaam, a special rainwater recycling system was set up [22].

Such simplification and energy-efficiency approach seems to be the inheritance of the design routines from the previous period, when Chinese architects used economic methods to achieve the general effects [14]. However, the higher requirements and international cooperation of the foreign-aided stadiums forced them to pursue a better design. The ETFE material and membrane structure were first used in China-designed/constructed stadiums in advance of Chinese domestic stadiums (**Figure 3**), when several years later, Beijing's "Water Cube" national natatorium shone its light using the same advanced material and structure. The authors believe that the experiment of the new material and structure in this China-aided stadium might provide a practical reference for the widespread use of the membrane in Chinese domestic stadiums after 2008, and also prepared BIAD for its future winning of the design of other China's foreign-aided stadiums, such as the Cote d'Ivoire stadium.

Figure 3. The bird view (left) and inside view (right) of the Tanzania National Stadium (Source: https://www.stadiumguide.com/tanzania-national-stadium/)

Tanzania National Stadium hosted its first events in 2007 after construction was completed, and was officially inaugurated in 2009. The stadium is at present the home of Tanzanian top sides Simba and Young Africans and has replaced the Uhuru Stadium as the national team's home ground. Behind the officials' rhetoric of friendship and cooperation, this stadium revealed the mode of China's aid in the 21st century, transferring from ideologically driven to market-oriented, which benefited both sides through Chinese exportation of designs, labor, and materials, and Tanzania's experiences in techniques and constructions through involvement.

3.2.2. Understanding of the local and the design between bio-influence: China-aided stadium in the Ivory Coast

Ivory Coast established its diplomatic relationship with China in 1983. It has received construction aid from China ever since, such as the Senator's Home, the Conference Hall of the Ministry of Foreign Affairs, hospitals, schools, etc. In recent years, the Ivory Coast has been one of Africa's most dynamic economies, and China has become its largest financing country and the third greatest trading partner.

The new China-aided stadium was in the northern entry gate of Abidjan, the Ivory Coast's informal capital, in the suburban areas of Ebimpe and Anyama. The new stadium was a part of the Olympic Village Ebimpe, a multi-use governmental-level project with a total land of 287 hectares, which was expected to become the centerpiece of the 2021 CAN. This China-aided Olympic stadium holds a 60,000-seat capacity and RMB 0.75-billion-yuan cost, covering 20 hectares. It is required to meet the standards of holding international high-level football, athletics, and rugby tournament games, and to be one of the largest and most modernized stadiums in Africa after its construction. Both the design and construction were put into bidding in domestic China by evaluations to determine the enterprises for the missions, as a result of the newly developed mechanism of China's foreign-aided construction project of the new era.

BIAD won the bid for designing the new national stadium project in 2015, with the concept of "African drum" (**Figure 4**). As introduced by its chief architect, Miao Liu, in our interview, the idea of a "drum" suddenly occurred to him when he was watching a football game at night while relaxing from the anxieties of working on the design of the stadium. The devotion of Africans to sports and the local culture filled the mind of the designer, and the concept was occasionally inspired by the sound of the game he was watching. The main image of this mega-structure looks similar to a drum with local ethnic characteristics. The designer believed that emphasizing symbolic and metaphorical forms might attract attention and help win the bid. Compared with the two other new stadiums to be constructed in the Ivory Coast, designed by foreign firms, the China-designed one holds relatively obvious characteristics shared with the new China-aided national stadium of Tanzania, identically designed by BIAD using the membrane roof in full circles and the waving-feeling supporting structural elements. The initial designs of this stadium also illustrate the influence Chinese architects received from Beijing's Olympic stadiums (Herzog and de Meuron's "Bird Nest" and "Water Cube," for instance) and their favor of the "skin" coverage in stadiums. Symbolization in the form of stadium "skins" was exported into China's overseas projects.

Figure 4. The initial winning design by BIAD of China-aided stadium in the Ivory Coast (Source: http://www.biad.com.cn/newspost.php?id=22)

However, the designers' favor of the local culture was actually misunderstood. The designers' favor of the local elements in their regional design approaches differed from what the recipient country wanted. With the opinions from the recipient country, the "African drum" concept was totally replaced by a new one dubbed "Arc de Triomphe" (Triumphal Arch). As one of the football world powers and the winner of CAN, this country's enthusiasm for football games represents its nation and spirit to a great extent. The designers had noticed the significance of football, but they expressed their feelings in a mild manner, which, however, the recipient country would like to portray in a contrary or more obvious way. The supporting structural elements of the facades were changed into tensioned lines upward from the base to imitate the shapes abstractly when people stretched their bodies with shoulders on shoulders as a metaphor of power and unity. The curved convergences of each two lines on top formed the Triumphal Arch in deformation shapes, which enabled the general appearance of the facades to echo the winning cup of CAN. Decorations on the facade were designed with orange interior walls, white rods, and green plinth, which match the colors of the national flag and highlight the national image of the recipient country, conforming to the identity of being a new nation.

This case illustrates that the recipient country started to care about what the gift from China would look like and involved itself in the design of the donated stadium. Although China's experts made the final decision in the bidding evaluation procedure in China, the recipient country's opinions may also influence the final results greatly through the revision process. Such opinions sometimes interfered with the design and even totally changed it. The revisions with strong opinions from the recipient country expanded the working time of the design from 2014 to 2017 (**Figure 5**).

Figure 5. China-aided stadium in the Ivory Coast: top, rendering; bottom, the stadium in construction (Source: top and bottom left, from BIAD; bottom right, from https://www.trendsmap.com/twitter/tweet/1152513481477906437)

It can be revealed from this stadium that standard improvement was made for China's foreign-aided stadiums after the 2010s. The China-aided stadium in Ivory Coast has three-layer stands and a full coverage membrane roof with a higher cost, multiple functions, and better design standards for international games. Funded through an EIBC (Export-Import Bank of China) loan, the construction was completed by Beijing Constructor Group by the end of 2019, after 34 months from the ground-breaking, well ahead of the 2021 CAN, which will be staged in Ivory Coast. The author regards this stadium as a turning point where the designs of China's foreign-aided stadiums transformed from economic ones to high-standard ones with regional expressions.

3.2.3. High-profile adaptation: New National Stadium of Cambodia

In the next decade, to improve the design efficiency and understanding from Chinese architects, a new adjustment was applied. The bid mechanism in China's foreign-aided construction projects starts to give recipient countries more discourse rights based on their presence as one of the final decision-makers to choose the design scheme. Most of these countries, which gained their independence from long-time colonization in the 20th century or even in the new century, tend to express a strong consciousness of nationality and culture in these stadiums. Chinese architects tended to accommodate such desires for winning the bid through more obvious expression and high-profile adaptation in architectural designs.

As one of China's best partners in the Asian area, Cambodia received a lot of aid from China since the 1950s [19,25–27]. In 2014, China agreed to finance one large stadium at a high cost of RMB 0.925 billion. It is China's most costly, largest-scale, and highest-standard foreign-aided stadium, as well as China's most expensive foreign-aided construction project. Different from China-aided stadiums of the previous period that emphasize economic efficiency [14], this stadium may equal the large stadiums of China's major cities and will be qualified for holding continental sports events, big international football games, and national activities, as the new national stadium of Cambodia.

For the main stadium, aided by China, the design was completed by Chinese design institutes through a bid in China. The bid evaluation by Chinese experts selected three design schemes in 2015. The alternative schemes were later introduced to the Cambodian representatives. However, the Cambodian representatives could not decide, so they reported the schemes back to the governmental authorities of their country. In the end, it was Prime Minister Hun Sen of Cambodia who made the final choice upon his preference for the design from IPPR. This stadium became the first China's foreign-aided stadium where the design was chosen by the head of state of the recipient country.

Covering 14.9 hectares' site areas, the main stadium accommodates 60,000 seats with 80,000 m^2 gross floor areas. Surrounded by the indoor stadiums designed by Cambodia's local architects, which shared unique features symbolizing the country's tradition and culture, the imported mega-structure needs to be accommodated with the existing local contexts. However, as the largest and most modernized stadium of the country and being designed by the donor's state-owned design institute, the architectural expression seems to be obviously different.

As explained by the architects from IPPR in our interview, the design scheme from IPPR won Hun Sen's preference for its adoption of multiple regional design approaches of cultural expression, combined with modern architectural language and technologies. The form of the stadium followed the roof ridge of traditional Cambodian buildings, as two giant bridge columns with unique shapes were set at both ends of the north–south axis of the main stadium, serving as the convergence support of steel cables of its roof membrane structure. The front appearance of the giant columns simulates the hand gesture of "namaste," which is a traditional Cambodian and Buddhist greeting, while their inclination coincided with the side shape of the structure to symbolize a dragon boat, a significant cultural element of Cambodia. Such imitation also existed in macro and micro scales, as such the ring-shape water system was located around the main stadium in the layout planning, as a reflection of Cambodia's traditional planning idea of "moat" . Furthermore, the decoration of special flower-shaped patterns was attached to the hollow grid plates of the gold-colored façade, as Cambodia's favorite traditional color.

The use of the concepts of "namaste" and "dragon boat" was favored by Cambodia's leader but generated challenges for architectural techniques, especially the structure and construction. It was achieved through a complex structural design with unique hyperbolic herringbone-shaped towers, a large-angle ring column cable membrane truss awning system, and a ring column-beam supporting structure system. The section of the herringbone-shaped tower was gradually reduced from the bottom to the top and closed at a height of 78 m, finally reaching a height of 99 m. The top height of the tower was formally designed to be 96 m, but later changed by Hun Sen to be 99 m for his belief in the good fortune behind the new number. The exterior of the tower is made of fair-faced concrete, while the middle body is hollowed with partitions set horizontally, wing-shaped steel bones, and a steel bar skeleton inside. The 65-m cantilever cable-stayed locking membrane awning takes the ring beam and ring columns as the support system, and the ring columns outward tilt at an angle of 67 to 79 degrees from the ground. BIM technology was used for the steel mold configuration of the beam and columns, and SAP simulation analysis was carried out to control the tension deformation. ETFE was used as the membrane material, which has been widely experimented with successfully in China. The metal curtain wall is composed of stainless-steel cable and 1.2-mm-thick aluminum-magnesium-manganese perforated plates, covered between the ring columns around the stadium as the facade. The landmark and symbolic form was achieved at the expense of high cost and complex structure, with the help of advanced computer software and materials for the ingratiation of the recipient country.

Additionally, climate-concerned regional designs were utilized in the stadium, as many previous China-aided stadiums did. To cope with the hot dry season and long rainy season in Cambodia, plenty of open space was reserved under the first-floor platform, forming an all-weather activity venue. The main facades of the stadium adopted aluminum perforated plates, and the awning used a membrane to meet the requirements of sheltering from sun and rain, and natural lighting and ventilation. The hollow plates also contributed to the natural ventilation of the stadium. All three-layer stands were overlapped to introduce more air flows. The under-back areas of some seats were hollowed for ventilation and cooling, similar to the designs in the Olympic Stadium of Cambodia in the 1960s [14]. The surrounding water system improved the microclimate of the site, which was also similar to the design of the Olympic Stadium of Cambodia. It seems that Chinese architects have gained experience in using these passive-efficient technologies through years of being involved in the foreign-aided projects, and through the knowledge learned from China-aided stadiums of the early period.

The construction began in June 2017 and was completed in October 2021. The Chinese firm is entirely responsible for construction, partnered with L.Y.P Group as the developer. This is the first time that the BIM was utilized in China’s foreign-aided construction projects, and it has been increasingly widespread in the design and construction of Chinese domestic projects. Chinese enterprises start to experiment with new techniques in overseas projects for profits and efficiency with more open attitudes authorized by the government of the new period (**Figure 6**).

Figure 6. Construction processes of China-aided Cambodia's new national stadium (Source: top two and middle left, from IPPR; middle right, the photo was taken by the author in 2019, in which the author was on a site investigation with Chinese engineers Mr. Baiqing Liu and Mr. Zhiwei Yin from IPPR; bottom, the stadium after construction was completed, from https://8bur.cscec.com/xwzx18/gskx18/202108/3381511.html?ivk_sa=1024320u)

4. Conclusion

Generally, in the new century, significant transitions have happened in the influential aspects of the design of China's foreign-aided stadiums. China's foreign aid policy and mechanisms generated considerable impacts on the designs, mainly for the utilization of tender and bid systems, and more diversified funding modes in these overseas aid projects. Another significant development was the increasing participation of the recipient countries in deciding the design due to the transformation of the mechanism, leading to the "recipient countries' opinions" being one of the most influential aspects. Chinese architects considered more about the regional aspects and the recipient countries' preferences in their designs. Cultural symbolizations become the main theme of the design concept and play critical roles in the designs of China's foreign-aided stadiums, especially in recent years. And the climate-oriented approaches were improved from low passive techniques of the previous period to high-tech ones of the new era. Regional aspects turn out to be the main course on the design table of Chinese architects.

China's foreign-aided stadiums bloomed with diversity and transitions in recent years, improved in the design level of such stadiums with the pursuit of high-standard stadiums by the recipient countries, and the great development of China's stadiums from the pre-Olympic period to the post-Olympic period. Although these stadiums cannot be considered the best Chinese stadiums, they are mostly the best stadiums in the recipient countries. Influenced by China's special construction aid mechanism and the recipient countries' opinions, these stadiums have become the products of bi-control and bi-choice of the donor and the recipient sides. The authors consider these designs of the new era to represent a unique critical regionalism with cultural and climate elements embedded in the mega-structures with modernism, adaptation, techniques, cultures, or combinations thereof.

Funding

This work was supported by the Scientific Research Project of Tangshan Normal University (20253125062), the Social Science Fund of Hebei Province (HB23YS016), and the Hebei Province Social Science Federation Fund (20230204059).

Disclosure statement

The authors declare no conflict of interest.

References

[1] Copper JF, 1979, China's Foreign Aid in 1978, School of Law, University of Maryland.

[2] Brautigam D, 2011, China in Africa: Seven myths. The Elcano Royal Institute/Real Instituto Elcano, Analysis of the Real Elcano Institute (ARI) 23/2011, Madrid, Spain 8.

[3] Brautigam D, 2011, The Dragon's Gift: The Real Story of China in Africa, Oxford University Press, New York.

[4] Will R, 2011, China's Stadium Diplomacy. World Policy Journal, 29(2): 36–43.

[5] Doytchinov G, 2012, Pragmatism, not Ideology: Bulgarian Architectural Exports to the "Third World." The Journal of Architecture, 17 (3): 453–473.

[6] Siamphukdee C, 2014, Introduction: "Export Architecture" and the Cold War. Journal of Export Architecture: A War of the Worlds – Cold War Projects abroad. Deakin University, Deakin, 1–2.

[7] Siamphukdee C, 2014, What have You Done? Typologies of Export Architecture. Journal of Export Architecture: A

War of the Worlds – Cold War Projects Abroad, Deakin University, Deakin, 6–8.
[8] Kacel E, 2010, This is not an American House: Good Sense Modernism in 1950s Turkey, in Lu D (ed.), Third World Modernism: Architecture, Development and Identity, Chapter 7, Routledge, London and New York, 165–185.
[9] Sorokina Y, 2012, Ghost of a Garden City, in Ritter K (ed), Soviet Modernism 1955–1991: Unknown History, Park Books, Switzerland, 179–192.
[10] Chang W, Xue CQL, 2018, A Brief Introduction to the Regional Design Attempt of China-aided Sports Buildings. Architecture and Culture, 10(175): 241–243.
[11] Chang W, Xue C, 2019, Towards International-China-aid Stadiums in the Developing World. Frontiers of Architectural Research, 5: 604–619.
[12] Chang W, Xue C, 2019, Cultural Expression in the Design of Aid Architecture - A Case Study of China-aided Architectural Practice in Cambodia. Urbanism and Architecture, 9(330): 26–29.
[13] Chang W, Xue C, 2020, Climate, Standard and Symbolization: Critical Regional Approaches in Designs of China-aided Stadiums. Journal of Asian Architecture and Building Engineering.
[14] Chang W, 2020, Aid, Sport and Architectural Exportation – a Study of China's Foreign-aided Stadiums from the 1950s to the 21st Century, City University of Hong Kong.
[15] Chang W, et al., 2024, From Labour Support to Design Support: Transition of China's Foreign Aid Stadiums from the 1950s to the 1970s. Journal of Asian Architecture and Building Engineering, 1: 1–18.
[16] Chang W, 2024, Architectural Development of China's Foreign-aided Stadiums: 1956–2019, Tianjin University Press, Tianjin.
[17] Strange A, Dreher A, Fuchs A, et al., 2017, Tracking Underreported Financial Flows: China's Development Finance and the Aid–Conflict Nexus Revisited. Journal of Conflict Resolution, 61(5): 935–963.
[18] The State Council of China, 2011, White Paper on China's Foreign Aid. Beijing, China.
[19] Liu F, 2016, The Historical Process and Realistic Development of China's Foreign Aid. Jinan Journal (Philosophy and Social Sciences), (2): 120–128.
[20] Kobayashi T, 2008, Evolution of China's Aid Policy. JBICI Working Paper No. 27, Japan Bank for International Cooperation Institute, Tokyo.
[21] Hubbard P, 2017, Aiding Transparency: What We Can Learn About China ExIm Bank's Concessional Loans. CGD Working Paper 126, Centre for Global Development, Washington, DC.
[22] Jiang H, 2007, National Stadium of Tanzania. Archicreation, 91(1): 50–55.
[23] Meng X, Yan R, 2011, Membrane Structure Construction Technique in Tanzania Stadium Engineering. Architectural Technique, 42(07): 628–630.
[24] Anonymous, 2006, Design and Experimental Analysis of Wanxiang Support in Tanzania National Stadium. Journal of Architectural Structure, 36(S1): 419–421.
[25] Gu J, 2004, China's Assistance to the Preservation of the Temple of Zhousa in Angkor, Cambodia. Proceedings of the Symposium on the Protection of Masonry Cultural Relics. China Association for the Protection of Cultural Relics.
[26] Deng Y, 2018, On China's Foreign Aid to Cambodia under the Belt and Road Strategy. Journal of Guangdong Agricultural and Industrial College of Technology, 34(01): 18–21.
[27] Sun G, 2012, Cooperation between China and Cambodia, Hand in Hand, People's Daily, March 30, 2012.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

The Impact of ESG Integration on REIT Performance: A Comparative Study Based on Quantitative Analysis

Dazuo Tan*

Dongbei University of Finance and Economics, Dalian 116025, Liaoning, China

**Author to whom correspondence should be addressed.*

Abstract: This paper systematically examines the impact of environmental, social, and governance (ESG) factors on the financial performance and long-term value of real estate investment trusts (REITs). Adopting comparative analysis as the quantitative research method, the paper selects representative cases of ESG-integrated REITs and traditional REITs at home and abroad, constructs a regression model, and compares projects from multiple key value dimensions, including yield, risk-adjusted returns, asset appreciation potential, financing costs, and market liquidity. The study finds that ESG-integrated REITs demonstrate significant advantages in long-term financial performance, risk resilience, and market valuation. Based on these findings, the paper proposes a series of policy recommendations, including improving ESG information disclosure standards, optimizing tax incentive mechanisms, and constructing an ESG evaluation system, to promote the high-quality and sustainable development of China's REIT market. The paper consists of five parts: introduction of the research problem, theoretical framework, research methods (data sources and model construction), quantitative comparative analysis between ESG-integrated REITs and traditional REITs, and conclusion with recommendations.

Keywords: Real estate; REITs; Regression model; Long-term performance; Sustainable development

Online publication: October 30, 2025

1. Introduction

In recent years, the significance of environmental, social, and governance (ESG) factors in the global capital market has become increasingly prominent. As an important tool connecting financial capital and physical assets, real estate investment trusts (REITs) have seen the impact of ESG integration on long-term performance become a focus of attention in both the academic and practical fields.

This study is based on two observations of the current REITs market: on the one hand, an increasing number of REIT managers are proactively disclosing ESG reports and implementing ESG strategies. On the other hand, some market participants remain skeptical about the actual returns of ESG investment, believing that it may increase operating costs without necessarily bringing corresponding financial benefits. This divergence makes it necessary for us to conduct scientific research and objectively assess the true impact of ESG factors on the performance of REITs, providing a scientific basis for investment decisions and policy-making.

2. Research significance

China's REIT market has developed rapidly since the pilot program was launched in 2020, but ESG integration is still in its infancy. By the end of 2024, among the 54 publicly offered REITs that have been listed in China, only about 20% have released dedicated ESG reports, and the quality and depth of disclosure vary greatly. In contrast, in leading global REIT markets such as the United States, Singapore, and Japan, ESG has become a mainstream investment consideration factor. According to GRESB (Global Real Estate Sustainability Assessment System) data, among the REITs evaluated in the Asia Pacific region in 2023, the annual total return of funds with high ESG scores was 2–3 percentage points higher than the industry average. This gap highlights the significant importance of studying ESG integration for the development of China's REIT market [1].

This study employs a comparative analysis method to select representative ESG-integrated REITs and traditional REITs cases both at home and abroad, and conducts quantitative comparisons from multiple dimensions such as financial performance, risk-adjusted returns, asset appreciation, financing costs, and liquidity. By constructing an assessment framework, the influence and mechanism of ESG factors on various key indicators of REITs are analyzed. At the same time, based on the empirical results, targeted policy suggestions are put forward to provide references for promoting the high-quality development of China's REIT market [2].

3. Theoretical framework

The development of ESG investment theory provides a solid theoretical foundation for studying the performance of REITs. Modern portfolio theory holds that ESG factors can influence asset returns and risk characteristics through multiple channels. Specifically in the REITs field, existing research has identified three main value creation paths: operational efficiency improvement, risk premium reduction, and valuation multiplier expansion. In terms of operational efficiency, properties with green building certifications (such as LEED and BREEAM) typically have higher energy efficiency. Data shows that the operating costs of such properties can be reduced by 15–20%, while the rental premium can reach 5–10%. From a social perspective, REITs that focus on employee benefits and community impact often enjoy lower employee turnover rates and higher tenant retention rates, thereby reducing vacancy costs and rental expenses. Well-governed REITs can reduce agency costs and increase the return on capital through transparent decision-making mechanisms and effective capital allocation [3].

From a methodological perspective, the current research on ESG-REITs mainly faces three major challenges: The first is the issue of ESG data quality and consistency, as the assessment standards of different rating agencies vary significantly; The second is the issue of endogeneity. REITs with outstanding performance may have more resources invested in ESG rather than ESG bringing about excellent performance. Thirdly, the long-term impact is difficult to capture. The value of ESG is often fully manifested over a period of 5 to 10 years, while most studies are limited by data and can only analyze shorter periods. This study will control these interfering factors through a carefully designed comparative analysis framework to enhance the reliability of the research conclusions [4].

Based on the literature review, we have constructed a theoretical framework for the value impact of ESG-REITs, which includes four core dimensions: (1) Financial performance, examining the impact of ESG on yield, dividend stability and growth potential; (2) Risk management, analyzing how ESG reduces operational risks, regulatory risks and reputation risks; (3) Capital acquisition: Research the role of ESG ratings in financing costs and investment attractiveness; (4) Long-term resilience, assessing the value of ESG integration in addressing climate change and market volatility. This multi-dimensional framework will guide subsequent empirical analysis to ensure that the research comprehensively captures the overall impact of ESG [5].

4. Research methods, data sources, and model construction

The sample selection criteria follow three principles: representativeness, data availability, and ESG diversity. The study selected 24 typical cases from major global REIT markets from 2019 to 2024, among which 12 were high ESG score REITs (experimental group) and 12 were ESG ordinary REITs (control group). The selection criteria for the high ESG group include: a GRESB rating of four stars or above, continuous release of ESG reports 4710, and obtaining green building certification or similar ESG honors. The selection of the control group ensures that it matches the experimental group in terms of asset type, region, and scale, but its ESG performance is at or below the industry average. The samples covered major REITs asset classes such as office, retail, logistics, industrial parks, and infrastructure to enhance the universality of the research conclusions [6].

The data collection work mainly relies on four sources: First, the publicly disclosed financial reports and ESG reports of REITs, which are used to extract data on financial performance and ESG practices. The second is the assessment results from professional ESG rating agencies (such as GRESB and MSCI), providing standardized ESG scores. The third type is market transaction data from financial databases (such as Bloomberg and Wind), which is used to calculate yields and valuation indicators. Fourth, secondary data from academic literature and industry research reports are used as supplementary references [7].

The Key Performance Indicators (KPI) system encompasses five dimensions and a total of 15 specific indicators: (1) Profitability, including return on equity (ROE), growth rate of working capital (FFO), and EBITDA margin; (2) Dividend performance: Examine the dividend yield rate, dividend growth rate and dividend stability (standard deviation); (3) Risk-adjusted return, calculate the Sharpe ratio, maximum drawdown and volatility; (4) Asset quality, assessing occupancy rate, rental growth rate and weighted average lease expiry (WALE); (5) Market valuation, analyzing the differences in stock price return rate, P/FFO multiplier and capitalization rate. These indicators together form a complete framework for evaluating the overall performance of REITs, capable of capturing the potential impact of ESG from various perspectives [8].

The statistical analysis method adopts a strategy combining descriptive statistics, correlation analysis, and multiple regression. Firstly, descriptive statistics are presented to show the mean, median, and distribution differences of the two groups of REITs in each performance indicator, and the potential impact of ESG is preliminarily observed. Then, Pearson and Spearman correlation tests were used to analyze the strength and direction of the association between ESG scores and various performance indicators. Finally, after constructing a multiple regression model to control for factors such as scale, leverage ratio, and asset type, the net impact of ESG on the performance of REITs was quantified. The model is set as follows:

$$P = \alpha + \beta_1 E + \beta_2 S + \beta_3 L + \beta_4 A + \varepsilon i$$

Among them, P (Performancei) represents various performance indicators of the *i*-th REITs, E (ESGScorei) is its standardized ESG score, S, L, A (Sizei, Leveragei, and AssetTypei) are control variables, and εi is the error term. By testing the significance and magnitude of the coefficient β1, the independent impact of ESG on performance can be determined [9].

The research limitations are mainly reflected in three aspects: first, the sample size is relatively limited, constrained by the availability of high-quality ESG data; second, the observation period may not be sufficient to capture the long-term impact of ESG; third, there are methodological differences in ESG scores themselves, and results from different rating agencies may be inconsistent. Based on these limitations, this paper has mainly selected the following research samples (**Table 1**), which are quite representative in the current global REITs market [10].

Table 1. Overview of research samples (some representative REITs)

Name of REITs	Country/region	Asset type	ESG performance	GRESB rating (2024)	Data source
GLP China Logistics Fund III	China	Logistics and warehousing	High ESG	Five-star	GRESB Report, Prologis China
Guotai Junan Dongjiu REIT	China	Industrial park	High ESG	Did not participate in GRESB but published an ESG report	Guotai Junan Dongjiu Company's ESG Report, Company Annual Report
Huaxia Yuexiu Expressway REIT	China	Infrastructure	Medium to high ESG	Did not participate in GRESB but released an ESG report	Huaxia Company's ESG Report, Company Annual Report
Simon Property Group	United States	Retail	Low ESG	Samsung	GRESB Report, Simon Property Group Annual Report
Mitsui Fudosan Logistics Park REIT	Japan	Logistics and warehousing	Low ESG	Two stars	GRESB Report, Mitsui Fudosan Co., Ltd. Annual Report

5. Quantitative comparative analysis of ESG-integrated REITs and traditional REITs

The financial performance shows significant differences (Table 2). The comparison between dividend payout capacity and stability further confirms the value of ESG. Data shows that the average dividend yield of REITs in the high ESG group is 5.6%, which is basically the same as 5.8% of the control group. However, the dividend growth rate and stability of the former are significantly better. Over the past five years, the average annual dividend growth rate of ESG-integrated REITs has been 4.2%, with a volatility (standard deviation) of only 1.8%, while the dividend growth rate of traditional REITs is only 2.7%, with a volatility of 3.5%. The case of Guotai Junan Dongjiu REIT stands out particularly. This industrial park REIT, through distributed photovoltaic projects and water-saving equipment, not only reduced operating costs but also enhanced the stability of cash flow. As a result, its available allocation amount completion rate in 2023 reached 107.4%, exceeding the forecast [11]. This stable dividend performance is particularly attractive to institutional investors who pursue long-term income, such as pension funds and insurance funds [12].

Long-term resilience indicators further highlight the strategic value of ESG. By analyzing Climate-related Financial Disclosures (TCFD) data, it was found that REITs in the high ESG group are significantly better prepared for physical risks and transition risks: 85% have conducted climate scenario analysis, while the control group is only 35%. In terms of carbon reduction targets, 70% of high ESG REITs have set Science-based Carbon targets (SBTi), while the proportion in traditional REITs is less than 20%. This forward-looking layout enables ESG-integrated REITs to take the initiative in the future low-carbon economy and reduces the risk of “stranded assets.” The photovoltaic project of Guotai Junan Dongjiu REIT generates over 10 million kilowatt-hours of electricity annually [13]. It not only reduces carbon emissions but also creates a new source of income through green power trading. As carbon prices rise and environmental protection regulations become stricter, the relative value of such low-carbon assets is expected to increase further [14].

Table 2. Comparison of key performance indicators between ESG-integrated REITs and traditional REITs (average from 2019 to 2024)

Indicator category	Specific indicators	ESG integrated REITs	Traditional REITs	Difference value	Magnitude of difference	Statistical significance (*P*-value)
Profitability	Return on Equity (ROE)	9.2%	7.5%	+1.7%	+22.7%	0.023
	FFO Growth Rate (CAGR)	6.8%	4.3%	+2.5%	+58.1%	0.015
	EBITDA profit margin	68.4%	63.1%	+5.3%	+8.4%	0.008
Dividend performance	Current dividend yield rate	5.6%	5.8%	-0.2%	-3.4%	0.650
	Dividend growth rate (CAGR)	4.2%	2.7%	+1.5%	+55.6%	0.032
	Dividend volatility (standard deviation)	1.8%	3.5%	-1.7%	-48.6%	0.018
Risk-adjusted return	Sharpe ratio	0.82	0.51	+0.31	+60.8%	0.006
	Maximum drawdown (2022)	-9.8%	-15.3%	+5.5%	+35.9%	0.012
	Annualized volatility	12.3%	16.7%	-4.4%	-26.3%	0.009
Asset operation	Average occupancy rate	96.4%	92.1%	+4.3%	+4.7%	0.009
	Rental growth rate (CAGR)	3.9%	2.4%	+1.5%	+62.5%	0.014
	Weighted average lease expiry (WALE)	4.7 years	3.9 years	+0.8 years	+20.5%	0.021
	Tenant renewal rate	78%	65%	+13%	+20.0%	0.007
Market valuation	P/FFO multiple	18.7x	15.3x	+3.4x	+22.2%	0.011
	Capitalization rate	5.2%	5.8%	-0.6%	-10.3%	0.025
	Proportion of shares held by institutional investors	62%	45%	+17%	+37.8%	0.004
Financing cost	Average debt interest rate	3.8%	4.5%	-0.7%	-15.6%	0.017
	Proportion of green bonds	41%	12%	+29%	+241.7%	0.002
ESG-specific indicators	Proportion of green building certification area	58%	19%	+39%	+205.3%	0.001
	Carbon emission intensity (kg CO_2/m^2)	23.5	36.2	-12.7	-35.1%	0.003
	Number of ESG controversy incidents	0.7	2.3	-1.6	-69.6%	0.005

6. Conclusion and suggestions

The empirical research results clearly support the assumption that ESG integration creates substantial value for REITs [15]. Through systematic comparative analysis of 24 typical cases from major global REIT markets from 2019 to 2024, the research found that REITs with high ESG scores significantly outperformed traditional REITs in multiple dimensions, such as financial performance, dividend payout capacity, risk-adjusted returns, asset operation quality, and market valuation. Specifically, the average ROE of ESG leading REITs is 170 basis points higher, the FFO growth rate is 250 basis points ahead, and the Sharpe ratio advantage is 0.31. At the same time, it demonstrates stronger market downturn protection capabilities and long-term resilience. These findings are consistent with the "win-win" theory of sustainable investment, indicating that ESG factors not only bring social benefits but also can be transformed into financial returns, creating alpha returns for investors.

The analysis of the value creation mechanism reveals the deep-seated reasons behind ESG advantages. Firstly, green building measures (such as energy-saving renovations and the utilization of renewable energy) directly reduce operating costs and increase the EBITDA margin. Secondly, ESG practices have enhanced asset attractiveness and tenant stickiness, as reflected in higher occupancy rates and longer lease terms. Secondly, a sound governance structure and risk management have reduced systemic risks, enabling REITs to perform more stably during market turmoil. Finally, ESG labels expand the investor base, especially attracting long-term institutional funds and generating valuation premiums. These mechanisms work together to form a closed loop of competitive advantages for ESG-integrated REITs.

Based on the research findings, this paper puts forward the following policy suggestions to promote the healthy development of China's ESG-REITs market:

Improving the ESG information disclosure framework: It is suggested that the China Securities Regulatory Commission (CSRC) work with industry associations to formulate a unified ESG disclosure guideline for REITs, mandatorily requiring public REITs to disclose ESG information in accordance with the principle of "explain if not complied," with key points including: (1) Environmental indicators: energy consumption intensity, carbon emissions, and the proportion of green building area; (2) Social indicators: Employee training investment, community participation projects, tenant satisfaction; (3) Governance indicators: Board independence, the proportion of executive compensation linked to ESG performance, anti-corruption measures. In the initial stage, a relatively low disclosure threshold can be set for infrastructure REITs and gradually extended to all types.

Building incentive-compatible tax policies: Drawing on international experience, design tax incentives for REITs with outstanding ESG performance: (1) For properties that have obtained green building certification, reduce or exempt property tax or urban land use tax; (2) A pre-tax additional deduction of 150% will be granted for ESG investment expenditures at the REITs level (such as energy-saving renovations). (3) For institutional investors holding ESG-REIT shares, income tax or value-added tax will be reduced or exempted. These measures can balance the short-term costs and long-term benefits of ESG investment, and encourage the market to spontaneously transform towards sustainability.

Developing a localized ESG assessment system: Led by authoritative institutions such as China Securities Index Co., LTD., develop an ESG rating method for REITs suitable for China's national conditions, with a focus on: (1) ESG issues specific to infrastructure REITs, such as ecological protection and rural revitalization; (2) The transformation path under China's "dual carbon" goals (3) Governance features such as the protection of small and medium-sized investors. At the same time, encourage the development of third-party ESG data providers to form a healthy competitive market ecosystem.

In conclusion, the core conclusion of this study is that ESG integration can create significant economic value for REITs, and this value has been verified in multiple dimensions such as financial performance, risk management, and long-term resilience. For China's REITs market, systematically promoting ESG practices is not only a response to the country's sustainable development strategy but also an effective way to enhance asset quality and international competitiveness. By improving the policy framework, fostering a market ecosystem, and strengthening international collaboration, China is expected to shape a REITs development model with its own characteristics in the global green finance wave, providing strong financial support for the low-carbon transformation of the real economy.

Disclosure statement

The author declares no conflict of interest.

References

[1] Xu Y, 2022, The Advantages and Strategies of REITs Practicing ESG Concepts. Bonds, (12): 39–43.

[2] Zhang Z, Cui J, 2024, Realize the Organic Integration of Consumer Infrastructure REITs and ESG to Jointly Promote the Development of the Real Economy. Sustainable Development Economic Review, (09): 37–39.

[3] Wang H, 2024, A Brief Analysis of the Current Practical Status and Optimization Suggestions of ESG Concepts in REITs. Real Estate World, (09): 33–37.

[4] Li Y, Sun Q, 2023, Application Scenarios and Practical Paths for Valuation Institutions to Implement ESG Concepts, China Real Estate Appraisers and Agents Association. Institutional Internal Governance and High-Quality Sustainable Development - Proceedings of the 2023 China Real Estate Appraisal Annual Conference, 744–747.

[5] Liu C, Li N, 2023, Practicing ESG Concepts to Promote High-Quality Development of the Housing Rental Industry, China Real Estate Appraisers and Agents Association, China Construction News, CCB Housing Service Co., LTD. Standardized Development and Best Practices - Proceedings of the China Housing Rental Development Forum. Shenzhen Shilian Land and Real Estate Appraisal Co., LTD. Shilian Evaluation Value Research Institute, 901–907.

[6] Wang K, 2024, Research on the Financing Effects of Public REITs from the Perspective of ESG, dissertation, Hebei University of Finance and Economics.

[7] Chen Y, Tang Y, Fang X, 2025, Research Hotspots, Trends and Framework of REITs Development with Chinese Characteristics. Accounting Friend, (10): 16–25.

[8] He Y, 2025, Practice of Innovative REITs Financing Models by Urban Investment Companies under the Background of Market-oriented Reform. Jiangsu Business Review, (04): 84–88 + 98.

[9] Wang C, 2025, Problems and Solutions of Integrating ESG Concepts into Financial Management. China Convention and Exhibition (China Conference), (16): 72–74.

[10] Zhou D, 2025, The Optimization Path to Solve the Financing Problem of Real Estate Investment Trust Funds. Property Market, (03): 50–52.

[11] Guo L, Li Y, 2024, Research on the Development of Real Estate Investment Trust Funds Facilitated by Blockchain Technology. Business Economics, (11): 96–99.

[12] Li B, 2024, Research on the Current Situation and Problems of REITs Issuance by State-owned Enterprises. China's Collective Economy, (29): 109–112.

[13] Zhang Z, 2024, Research on Financing Risk of Investment Trust Funds: A Case Study of Real Estate Enterprise A.

Market Weekly, 37(27): 72–75.
[14] Zheng L, 2024, Analysis of Key Points in the Development of Real Estate Investment Trust Funds. Real Estate World, (13): 122–124.
[15] Han W, 2024, Research on Tax Policies for Real Estate Investment Trust Funds in China, dissertation, Lanzhou University of Finance and Economics.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Optimization of the Construction Organization Design of Office Building Projects

Liang Chen*

Shenzhen 518000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: This paper focuses on the construction organization design of office building projects. It elucidates its concept, core elements, and characteristics, highlighting the shortcomings of traditional designs. The paper introduces the improvement effects of technologies such as prefabricated curtain walls, the collaborative optimization role of BIM technology, and various optimization methods, including the establishment of work breakdown structures and the creation of progress deviation warning systems. It also touches on aspects like green construction and risk management. Finally, it emphasizes the significance of optimizing construction organization design, addresses research deficiencies, and looks forward to future research directions.

Keywords: Office building project; Construction organization design; Optimization

Online publication: October 30, 2025

1. Introduction

With the acceleration of urbanization, the construction of office buildings is increasing day by day. The *Guiding Opinions on Improving the Quality Assurance System and Enhancing the Quality of Construction Projects*, released in 2019, emphasized the importance of improving the quality of construction projects. As a key document guiding construction, construction organization design is crucial for the construction quality and efficiency of office building projects. It covers various aspects such as project overview, project organizational structure and division of responsibilities, construction deployment, analysis of key and difficult construction points, and corresponding measures. However, traditional construction organization design has shortcomings in resource allocation and process connection, and technologies such as BIM and prefabricated curtain walls provide support for its optimization. At the same time, the reasonable construction of work breakdown structures and the establishment of a schedule deviation warning system play an important role in schedule management. In addition, the staggered allocation of labor and site layout also affects the implementation of the project. All of these need to be comprehensively considered in the construction organization design to meet the needs of office building construction.

2. Overview of construction organization design for office building projects

2.1. Basic concepts and characteristics of construction organization design

Construction organization design is a comprehensive document that guides the technical, economic, and organizational aspects of various construction activities throughout the entire construction process. It is developed based on engineering projects, relevant regulations, standards, and engineering design documents, combined with specific conditions and requirements of engineering construction. The core elements include project overview, construction deployment, construction schedule, construction preparation and resource allocation plan, main construction methods, construction site layout, and main construction management plan. The construction organization design of office building projects has its own characteristics. Office buildings require efficient and rational planning in terms of space utilization to meet the needs of office functions. In terms of vertical transportation, efficient transportation of personnel and materials should be considered. Curtain wall construction should pay attention to aesthetics and safety. These particularities need to be fully reflected in the construction organization design [1].

2.2. The necessity of optimization and practical challenges

Traditional construction organization design has shortcomings in resource allocation and process connection. In terms of resource allocation, there may be issues such as material waste, idle or insufficient equipment, leading to increased costs and low construction efficiency [2]. Unreasonable arrangements in the process connection may cause construction delays, affecting the overall progress of the project. Taking the super high-rise office building project as an example, its complex structure and numerous construction processes require higher requirements for construction organization design. If resource allocation is improper, such as insufficient pumping equipment required for high-rise concrete pouring, it will seriously affect the construction progress. Unreasonable process connections, such as the overlapping and chaotic construction of the main structure and internal decoration processes, will increase the difficulty, quality, and safety risks of construction, highlighting the urgent need for optimization of construction organization design.

3. Optimization strategies from the perspective of technical management

3.1. Innovation in key technology applications

The core technologies of prefabricated curtain wall installation and deep foundation pit reverse construction have important improvement effects on the construction organization design of office building projects [3]. Prefabricated curtain wall installation technology can improve the efficiency and quality of curtain wall installation, reduce on-site workload, lower safety risks, and facilitate industrial production and quality control. The reverse construction method for deep foundation pits can effectively solve problems such as narrow construction sites and complex surrounding environments. By arranging the construction sequence reasonably, it is possible to achieve simultaneous construction above and below ground, shorten the construction period, improve land utilization efficiency, and have minimal impact on the surrounding environment. The innovative application of these key technologies provides strong support for the optimization of construction organization design in office building projects.

3.2. Collaborative optimization of BIM technology

BIM technology plays an important collaborative optimization role in the construction organization design of office building projects [4]. In terms of construction simulation, BIM can be used to virtually model and analyze the construction process, identify potential problems in advance, optimize the construction sequence and process, and improve construction efficiency and quality. In the comprehensive application of pipelines, BIM can integrate various pipeline information, perform collision detection, effectively solve pipeline conflicts, and plan spatial layout reasonably. For progress visualization, BIM can associate construction progress with models, visually display the progress of the project, facilitate construction management personnel to adjust the construction plan in a timely manner, and ensure that the project is completed on time. These applications greatly enhance the scientificity and rationality of construction organization design and promote the smooth implementation of office building projects.

4. Optimization path of progress management system

4.1. Dynamic optimization of a schedule plan

4.1.1. Work breakdown structure decomposition and critical path

Building a reasonable work breakdown structure is crucial in office building projects. By breaking down the project work in detail, clarifying the various work packages and their interrelationships, a foundation is laid for schedule management [5]. Optimize the cross-operation process between mechanical and electrical installation and the main structure using the critical chain method. The critical chain method considers resource constraints and project uncertainty. By identifying critical chains and setting buffer times, it can effectively avoid schedule delays caused by resource conflicts and uncertainty factors. On the basis of work breakdown structure decomposition, combined with the critical chain method, it is possible to better dynamically optimize the project schedule, ensure that all work is carried out in an orderly manner according to the plan, improve the construction efficiency and quality of office building projects, and achieve the optimization of the schedule management system.

4.1.2. Construction of progress warning mechanism

The key to optimizing the schedule warning mechanism is to establish a dynamic adjustment model based on a BIM+5D design schedule deviation warning system. By utilizing the visualization and information integration advantages of BIM, combined with the time dimension information of 5D, real-time monitoring of project progress can be achieved [6]. By setting a reasonable progress deviation threshold, the system can issue timely warnings when there is a deviation between the actual progress and the planned progress. At the same time, establish a dynamic adjustment model to quickly adjust the schedule based on warning information. This model can comprehensively consider various factors such as resource allocation and process logic relationships to generate optimized schedule plans, ensuring that the project can proceed smoothly according to predetermined goals and effectively improving the efficiency and accuracy of schedule management.

4.2. Resource-balanced allocation method

4.2.1. Tower crane scheduling optimization model

Establishing a multi-tower crane collaborative operation model based on a genetic algorithm is the key to solving the bottleneck of vertical transportation of materials in super high-rise buildings. This model encodes the operational parameters of tower cranes, transforming the scheduling problem of tower cranes into a chromosome encoding problem in genetic algorithms. By utilizing the selection, crossover, and mutation operations of genetic algorithms, the scheduling scheme of tower cranes is continuously optimized to achieve high efficiency and balance in vertical material transportation. At the same time, consider the safety distance and operating range between tower cranes to avoid collisions and interference between them. Through simulation experiments and practical application verification, this model can effectively improve the utilization rate of tower cranes, reduce material transportation time, improve construction efficiency, and provide strong support for the progress management and resource balance allocation of office building projects [7].

4.2.2. Dynamic allocation of labor force

The staggered allocation of labor for curtain wall engineering and interior decoration is crucial for the construction of office buildings [8]. By analyzing the process characteristics and time nodes of curtain wall engineering and interior decoration, reasonable labor input can be arranged to avoid labor conflicts during peak construction periods between the two. Using the PDCA cycle for continuous improvement, develop a detailed plan for staggered labor allocation during the Plan phase; During the Do phase, strictly allocate labor according to the plan; Check phase, comparing the actual and planned differences; In the Act phase, adjust the configuration plan based on the inspection results, continuously optimize the dynamic allocation of labor, improve construction efficiency, and ensure project progress.

5. Comprehensive optimization plan for engineering planning

5.1. Key control points in early planning

5.1.1. Site dynamic planning strategy

Developing a phased site layout plan is crucial for solving the problem of narrow construction sites in urban office buildings [9]. It is necessary to comprehensively consider the characteristics and needs of each stage of construction and plan the site use reasonably. During the foundation construction phase, emphasis is placed on arranging material stacking and mechanical equipment parking areas to ensure the smooth progress of the foundation project. As the main construction progresses, adjust the site layout to provide sufficient space for materials such as formwork and steel bars, while setting up safety passages and protective facilities. During the decoration phase, it is necessary to reserve areas for material processing and finished product stacking to avoid interference with other construction areas. By dynamically planning the site, the utilization rate of the site can be improved to ensure construction progress and safety.

5.1.2. Optimization of a material supply system

Build a material entry plan under the JIT procurement model to meet the immediate needs of office building construction, improve the accuracy and timeliness of material supply, and reduce inventory costs and waste [10]. At the same time, establish an emergency reserve mechanism to reserve a certain amount of key materials for potential material supply interruption risks, such as natural disasters, supplier issues, etc. This not only ensures the continuity of the project, but also reduces the impact on project progress and quality in case of emergencies. Reasonably determining the types and quantities of emergency reserve materials requires comprehensive consideration of factors such as the characteristics of the project, the importance of the materials, and the stability of the supply market.

5.2. Collaborative management of the construction process

5.2.1. Multi-disciplinary coordination mechanism

In office building engineering, BIM-based multi-disciplinary collaborative management of mechanical and electrical, decoration, and curtain wall is crucial. By establishing a unified BIM model, each profession can integrate its own design information into it. Mechanical and electrical majors can accurately plan pipeline layouts in models to avoid conflicts with decoration and curtain wall structures. The decoration profession can determine space utilization and decoration details based on models, while considering the installation and maintenance space of mechanical and electrical equipment. The curtain wall profession designs the exterior facade based on the model to ensure a reasonable connection with the internal structure, mechanical and electrical components, and decoration. During the construction process, BIM models are used for real-time monitoring and adjustment, allowing professionals to communicate and coordinate in a timely manner, solve problems that arise, improve construction efficiency and quality, and ensure the smooth progress of office building projects.

5.2.2. Overall planning for green construction

In terms of overall planning for green construction, measures such as dust control and noise control need to be integrated. For dust control, fences can be set up at the construction site to cover exposed ground and materials, and the construction site should be regularly watered to reduce dust. At the same time, car wash basins should be set up at vehicle entrances and exits to prevent vehicles from carrying mud on the road. Regarding noise control, arrange construction time reasonably and avoid high noise operations during residents' rest time. Select low-noise construction equipment and conduct regular maintenance. Take shock-absorbing and noise-reducing measures for construction equipment, such as installing shock-absorbing pads, mufflers, etc. Through the comprehensive application of these measures, green construction can be achieved, reducing the impact on the surrounding environment and ensuring the continuity of office building construction.

5.3. Construction of a risk control system

5.3.1. Risk identification and assessment

During the construction process of office building projects, it is necessary to establish a risk matrix for high-altitude operations and equipment installation. For high-altitude operations, there may be risks such as personnel falling and object strikes. When identifying, factors such as work height, protective measures, and weather conditions should be considered. Assess its risk level, such as high altitude and insufficient protection, resulting in a higher risk level in adverse weather conditions. For equipment installation, risks include equipment damage, installation errors, etc. Consider the weight of the equipment, the complexity of the installation process, and the skills of the operators. When the installation process of large equipment is complex and the skills of operators are insufficient, the risk is greater. By detailed identification and assessment of these risks, a unique risk matrix for office building projects is constructed to provide a basis for subsequent risk control.

5.3.2. Design of emergency response plan

It is crucial to establish emergency response plans for office building construction projects. For extreme weather, pay attention to the weather forecast in advance. Before rainstorms, gales, and blizzards, reinforce, protect, or remove tower cranes, scaffolds, and other equipment on the construction site, and conduct safety inspections on temporary buildings to ensure that workers are transferred to safe areas. In addition, a sound health and safety response team should be established, equipped with professional first aid personnel and necessary first aid equipment, in order to respond quickly in emergency situations, prevent and respond to risks such as heatstroke, frostbite, and other environmental health hazards, and ensure the safety and physical health of construction personnel. Through the above measures, the ability of office building construction to cope with extreme weather and other sudden risks will be comprehensively improved, providing a solid guarantee for the safety, stability, and smooth progress of the construction process.

6. Conclusion

Optimizing construction organization design is of great significance for office building projects. By planning the construction process and resource allocation reasonably, the construction efficiency has been significantly improved and the construction period has been shortened. At the same time, the effect is significant in cost control, reducing unnecessary expenses in materials, labor, and other aspects. However, there are certain shortcomings in current related research, such as insufficient depth of application of intelligent algorithms, which have not fully tapped into their potential in optimizing construction organization design. Looking ahead to the future, digital twin technology shows promising application prospects. Integrating it with construction organization can simulate the construction process more accurately, identify and solve problems in advance, further improve the scientificity and rationality of construction organization design, and promote the improvement of construction quality and efficiency of office building projects.

Disclosure statement

The author declares no conflict of interest.

References

[1] Li X, 2020, Exploration of Optimization Ideas for Construction Organization Design of Construction Projects. Residential and Real Estate, (27): 102–103.

[2] Cai X, 2015, Optimize Construction Organization Design and Determine Project Cost Reasonably. Northeast Water Resources and Hydropower, 33(02): 25–26.

[3] Luo J, 2014, Research on the Preparation and Optimization of Construction Organization Design for the Ground Engineering of Xiaoshan Airport Airfield, dissertation, Southwest Jiaotong University.

[4] Zhang S, 2017, Research on Optimization of Construction Organization Design Based on Network Planning Technology, dissertation, Chengdu University of Technology.

[5] Hu H, 2017, A Preliminary Analysis of Optimizing Construction Organization Design and Reasonably Determining Engineering Cost. Journal of Sichuan Vocational and Technical College, 27(01): 164–166.

[6] Wei Z, 2016, Research on Optimization of Construction Organization Design in Construction Projects. Building Engineering Technology and Design, (6): 1935–1935.

[7] Wei W, 2019, Optimizing Construction Organization Design to Reduce Engineering Costs. China Real Estate Industry, (2): 212.

[8] Yan G, 2013, Discussion on Optimization of Construction Organization Design in Construction Projects. Urban Construction Theory Research (Electronic Version), (7): 1–5.

[9] Liu G, 2014, Research on Optimization of Construction Organization Design in Building Engineering. Urban

Construction Theory Research (Electronic Version), (5).
[10] Wang J, 2018, Application of Optimizing Construction Organization Design in Reasonably Determining Engineering Costs. Smart City, 4(18): 137–138.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Study on the Path of Green Construction and Intelligent Buildings in Promoting the Sustainable Development of the Construction Industry

Yue Liu*

Hainan Vocational University of Science and Technology, Haikou 571126, Hainan, China

**Author to whom correspondence should be addressed.*

Abstract: Against the background of energy conservation and emission reduction, green construction and intelligent buildings have become an inevitable trend in the transformation of the construction industry. They effectively reduce environmental damage and pollution caused by construction projects during the construction process, improve the comfort and health of buildings, and are conducive to promoting the sustainable development of China's construction industry. This paper analyzes the relationship between green construction and intelligent buildings, examines the dilemmas faced by the integrated development of green construction and intelligent buildings, and proposes measures such as optimizing architectural design schemes, advancing technological innovation, improving energy utilization efficiency, actively applying BIM technology, and strengthening building lifecycle management, so as to promote the sustainable development of China's construction industry.

Keywords: Green buildings; Intelligent buildings; Construction industry; Development dilemmas; Sustainable development

Online publication: October 30, 2025

1. Introduction

With the acceleration of urbanization, environmental pollution and energy shortage have become increasingly prominent, and the construction industry has become one of the main sources of environmental pollution and carbon emissions. Faced with this severe challenge, the construction industry, with sustainable development as its goal, is accelerating technological innovation in green buildings and intelligent buildings, promoting green and environmentally friendly building materials, and reducing building energy consumption and carbon emissions. It also uses new technologies such as BIM and the Internet of Things to strengthen construction management, realize intelligent management of building materials, construction processes, and quality management, improve energy utilization efficiency, and thereby enhance the construction quality and comfort of construction projects. This paper clarifies the relationship between green construction and intelligent buildings, strives to balance environmental protection, resource utilization, and ecological conservation, strengthens the full-cycle management of construction projects, promotes the sustainable development of the construction industry, and provides references for urban construction.

2. The correlation between green construction and intelligent buildings

Green construction and intelligent buildings are research hotspots in the modern construction field, and also important foundations for the sustainable development of the construction industry. Their correlation lies in jointly promoting the sustainable development of the construction industry and implementing energy conservation and emission reduction goals. Green construction focuses more on handling the relationships between environmental protection, resource conservation, and ecological balance during the construction process of building projects, while intelligent buildings emphasize the use of new technologies such as artificial intelligence and mechanical automation to achieve full-cycle management of building projects. The two have a mutually promoting and complementary relationship, jointly driving the sustainable and high-quality development of the construction industry [1].

Firstly, different from traditional architectural design and construction models, green construction focuses more on the selection of environmentally friendly materials to reduce environmental damage and construction waste. Intelligent buildings, on the other hand, use BIM technology, big data, etc., to manage the ventilation, lighting, power, and air conditioning systems in buildings. They automatically adjust indoor lighting and air conditioning systems based on indoor and outdoor temperature, light, and other factors to optimize resource allocation [2]. For example, in intelligent buildings, sensors are used to automatically adjust indoor lighting brightness and air conditioning temperature, and environmentally friendly external wall insulation materials are selected, thereby reducing energy consumption. It can be seen that intelligent buildings and green construction are highly consistent in terms of energy conservation and emission reduction goals.

Secondly, the sustainable design concept in green construction can only be realized with the support of intelligent building technologies. Intelligent buildings use artificial intelligence, big data, and other technologies to monitor and manage the entire process of building projects, realizing the rational use of electrical and water resources, reducing waste of electricity and water, and lowering the overall energy consumption of buildings. This thus implements the concept of green construction and achieves the goal of sustainable development in the construction industry, reflecting the complementary relationship between the two. For example, a certain intelligent building adjusts the air conditioning temperature in summer and winter through a central control system and adjusts the brightness of lighting according to light conditions, avoiding resource waste and effectively reducing various costs [3].

Thirdly, intelligent buildings can collect energy consumption data such as electricity, water resources, and gas, and analyze the data to provide accurate data references for green construction and promote the improvement of green construction technologies [4]. For example, intelligent buildings can collect energy consumption data of ventilation, power, and air conditioning systems, conduct quantitative analysis on the green energy-saving effect of buildings, and provide guidance for the innovation and improvement of subsequent green construction technologies.

3. Difficulties faced in the development of green construction and intelligent buildings

3.1. Challenges in technology integration and implementation

Green construction and intelligent buildings still face numerous challenges in the process of technology integration and implementation, which are mainly reflected in the integration and coordination between different technologies and systems, placing higher demands on practitioners in the construction industry. In green construction, it is necessary to integrate different types of energy-saving and environmentally friendly materials. Construction workers are required to select materials such as external wall insulation materials and solar panels based on local environmental characteristics and project requirements. For intelligent buildings, however, technologies like automatic control, artificial intelligence, and big data need to be integrated into architectural design and operation and maintenance management [5]. These technologies span multiple fields and not only require technical adaptability—such as the compatibility and adaptability between BIM technology and automatic control systems, and between insulation materials and building appearance design—but also increase the difficulty of developing green construction and intelligent buildings invisibly.

3.2. Challenges in cost and economic benefits

Green construction and intelligent buildings require relatively high initial investment and have a long payback period. Energy-saving effects are difficult to yield returns in the short term, which imposes a considerable economic burden on investors. For example, green construction uses environmentally friendly and energy-saving materials, whose cost is much higher than that of traditional building materials, increasing the project cost invisibly and deterring many investors. The central control systems installed in intelligent buildings are also expensive; they require regular replacement and debugging of intelligent equipment, and the subsequent maintenance costs are relatively high, posing a severe challenge to investors [6]. In summary, the investment returns of green construction and intelligent buildings are full of uncertainties, which have become an important factor restricting their integrated development and also affect the sustainable development of the construction industry.

3.3. Difficulties in building lifecycle management

In the development of green construction and intelligent buildings, building lifecycle management is an important and complex challenge. It is reflected in the overall management from the design, construction, to operation and maintenance stages, which needs to be carried out based on the environment, project budget, etc. For example, in the design stage, it is necessary to select environmentally friendly materials according to the project budget and environmental characteristics to ensure high resource utilization, low carbon emissions, and low energy consumption throughout the building’s lifecycle. Materials with durability, low maintenance costs, and recyclability should be prioritized. In the construction stage, investors and constructors must adhere to the concept of energy conservation and emission reduction, use BIM software to accurately calculate material consumption, reduce material waste, and promptly identify problems in the construction process to avoid rework—thereby controlling project costs and laying a good foundation for subsequent operation and maintenance [7].

4. Paths for green construction and intelligent buildings to facilitate the sustainable development of the construction industry

4.1. Promoting technological innovation and integration, and practicing the concept of green construction

Universities, research institutes, and enterprises should strengthen cooperation, jointly develop energy-saving and environmental protection materials as well as intelligent management technologies, promote technological innovation and integration, and accelerate the integration of green construction and intelligent buildings, thereby advancing the sustainable development of the construction industry. Firstly, universities, research institutes, and enterprises should actively develop new-type environmentally friendly building materials, energy-saving technologies, and intelligent systems to reduce the cost of environmentally friendly building materials, enabling more construction enterprises to adopt such materials, thus reducing construction waste and energy consumption. For instance, multiple parties can jointly develop high-efficiency, environmentally friendly, and thermal insulation materials, reducing the thermal conductivity of building materials to 0.02 W/(m·K) to minimize heat loss of buildings, thereby accelerating the innovation of building exterior wall insulation materials [8]. Secondly, universities and enterprises can jointly develop intelligent building management systems, improving the compatibility and user-friendliness of these systems to meet the intelligent building management needs of residential buildings, public buildings, and enterprises, thus reducing the energy consumption of electricity, gas, and water resources. For example, the two parties can develop intelligent control systems that collect data such as outdoor illumination, temperature, and humidity through sensors, and intelligently adjust indoor air conditioning and lighting systems to achieve the management goals of intelligent management and reduced energy consumption. Finally, all parties should actively integrate different technologies to promote the integration of green construction and intelligent construction technologies, and perfectly integrate solar panels and wind power generation equipment with building structures and architectural design, so as to enhance user experience and artistic design effects. For example, combining wind power generation, solar panels with traditional architectural design to achieve "self-sufficiency" can truly reduce the electrical energy consumption of buildings, improve the aesthetics and practicality of buildings, and realize the goal of sustainable development of the construction industry [9].

4.2. Optimizing architectural design schemes and implementing the concept of energy conservation and emission reduction

Architectural design is the prerequisite for realizing green construction and intelligent buildings, laying a solid foundation for intelligent construction, full-cycle management, and the transformation of the construction industry towards energy conservation and emission reduction. Firstly, architects should uphold the concepts of green construction, energy conservation, and emission reduction, carry out design based on the ecological environment of the construction project site and project budget, minimize damage to the natural environment, adopt ecological architectural design principles such as rational energy utilization, environmentally friendly materials, and efficient water resource utilization, and select environmentally friendly materials and intelligent equipment to reduce the emission of greenhouse gases such as carbon dioxide [10]. In addition, designers should also reasonably plan building space, optimize spatial layout, and make full use of inherent conditions such as natural lighting and ventilation to ensure indoor ventilation and natural lighting of buildings, thereby reducing the waste of water and lighting resources. Secondly, designers should comprehensively consider the orientation, ventilation, and lighting of buildings and building materials, reasonably plan indoor layout and building orientation, and make full use of natural light and ventilation to meet the residents' needs for natural ventilation and lighting, reducing residents' use of air conditioners and lighting fixtures, thus achieving the goal of energy conservation and emission reduction. At the same time, designers should also try to select recyclable building materials, such as clay bricks, ecological bricks, plant-based polyurethane foam boards, and polycarbonate boards. These materials can not only reduce the generation of construction waste but also realize the recycling of building materials, reducing resource consumption, thereby promoting the sustainable development of the construction industry [11].

4.3. Improving energy utilization efficiency and reducing environmental pollution

Construction enterprises should establish the concept of sustainable development, improve energy utilization efficiency, vigorously promote and apply solar energy, energy-saving lighting equipment, and intelligent control systems, reduce energy consumption and carbon emissions during the construction and operation and maintenance phases of buildings, minimize environmental damage and pollution, and achieve sustainable development goals. During the construction phase, construction personnel can choose recyclable or renewable building materials to reduce resource exploitation and consumption. For example, selecting high-efficiency thermal insulation materials, energy-saving glass curtain walls, and high-performance doors and windows can improve construction quality while reducing construction waste and carbon emissions [12]. In intelligent buildings, construction enterprises can install solar photovoltaic panels on the roofs and walls of buildings, ensure the stability and safety of the panels, convert solar energy into electricity, and use clean energy to power the buildings, thereby reducing the consumption of electrical resources. In addition, construction units can install light sensors, temperature sensors, and video monitoring equipment indoors, set indoor temperature and brightness according to the season, and automatically adjust the brightness of indoor lighting fixtures and air conditioning temperature through intelligent building control systems. This not only reduces management workload but also enables intelligent regulation, thereby lowering energy consumption and accelerating the transformation of the construction industry towards sustainable development.

4.4. Scientific application of BIM technology to achieve intelligent management

BIM technology can help construction enterprises understand the requirements of various links, such as project design, budget management, material management, and operation and maintenance management, realize data sharing and real-time update of construction information, thereby improving the efficiency and quality of project construction. First, construction enterprises can build a BIM technology management platform, present the effect of design drawings through a 3D visualization model, analyze the indoor and outdoor environment of buildings, the utilization of building materials, and the planning of indoor space layout, flexibly adjust construction plans to ensure the construction progress, and thus reduce energy consumption during the construction process. For example, construction personnel can use BIM software to conduct virtual simulation tests on indoor natural lighting, sunlight, seismic coefficient, etc. of buildings, automatically generate civil engineering, mechanical and electrical equipment, and engineering organization construction plans, timely adjust existing problems, and obtain optimal green construction plans and intelligent building design drawings, thereby reducing energy consumption during construction and operation [13]. Second, investors can use BIM software for building operation and maintenance management, connect the Internet of Things, big data, and BIM software to realize real-time supervision of the building's internal ventilation ducts, gas, fire protection, electricity, lighting, and air conditioning systems. They can also install solar panels on the roof to use clean energy for power supply, and intelligently adjust lighting, ventilation, and air conditioning systems according to seasons, weather, etc., so as to improve the living and office experience of owners, reduce the cost of building operation and maintenance management, lay a good foundation for the development of green construction and intelligent buildings, and promote the sustainable development of the construction industry [14].

4.5. Strengthening the management of building lifecycles and promoting the sustainable development of the construction industry

Construction enterprises should integrate green construction and intelligent buildings throughout the stages of design, construction, demolition, and material recycling, promptly address problems in each link, and reduce energy consumption to achieve sustainable development goals. Firstly, at the design stage, architectural designers should adopt the Life Cycle Cost Analysis (LCCA) method to scientifically evaluate the costs of project design, construction, operation, demolition, and material recycling, optimize project cost management, and select environmentally friendly materials and energy-efficient equipment with low operating costs and high initial investment returns. Secondly, during the construction phase, contractors should make good use of artificial intelligence and BIM technology, adopt modular management, actively promote the concept of prefabricated buildings, accurately control the usage of construction materials, improve construction efficiency, and shorten the construction period on the basis of ensuring project quality, thereby reducing project energy consumption [15]. In addition, enterprises should strengthen the management of the building operation and maintenance phase, and use intelligent building management systems to adjust ventilation, power, air conditioning, and lighting systems to ensure the stable operation of each system. Finally, enterprises should do a good job in building demolition and material recycling management, make plans before building demolition, identify recyclable and reusable construction materials, and target recycling these materials to provide recyclable materials for new buildings, thus realizing the sustainable development of the construction industry.

5. Conclusion

In summary, green construction and intelligent buildings are important measures for the sustainable development and transformation of the construction industry, as well as important channels for implementing the concept of energy conservation and emission reduction, and their importance is self-evident. Construction enterprises should deepen cooperation with universities and research institutes, actively develop new environmentally friendly, efficient, and high-performance construction materials, promote technological innovation and integration, cultivate compound construction talents, and drive the construction industry towards a more environmentally friendly, energy-saving, intelligent, and sustainable direction. Furthermore, construction enterprises should implement the concepts of green, energy-saving, environmental protection, and intelligent development in links such as design, construction, operation and maintenance management, and construction material recycling, strengthen full-cycle management, and achieve sustainable development goals.

Disclosure statement

The author declares no conflict of interest.

References

[1] Yang T, 2024, Discussion on the Application of BIM Technology in the Structural Design of Green Intelligent Buildings——Taking the Energy-Saving Design of a Green Office Building Project in Hangzhou as an Example. Chinese Residential Architecture, 17(08): 43–45.

[2] Xiao W, 2024, Exploration on the Application of Intelligent Building Electrical Technology in Energy Conservation and Emission Reduction of Green Residences. Chinese Residential Architecture, 17(07): 30–32.

[3] Song T, 2024, Application of BIM Technology in the Structural Design of Green Intelligent Buildings. Residence, (29): 113–116.

[4] Yang Q, Huang L, Zhang B, 2024, Discussion on the Integration and Development Strategy of Green Buildings and Intelligent Buildings. Stone Material, (09): 98–100.

[5] Wang Y, 2024, Exploration on the Integrated Development of Intelligent Buildings and Green Buildings in the Real Estate Market. China Venture Capital, (25): 48–50.

[6] Shen Y, 2024, Cultivating New-Quality Productive Forces to Promote Green, Intelligent and Innovative Development of the Industry——The 4th Green Construction and Intelligent Building Innovation Conference Successfully Held. Green Construction and Intelligent Building, (07): 4–5 + 9.

[7] Sun Y, 2024, Research on the Path of Green Construction and Intelligent Buildings Assisting the Sustainable Development of the Construction Industry. Urban Architectural Space, 31(S1): 147–148.

[8] Feng J, 2021, Exploration on the Key Elements of the Integrated Development of Green Buildings and Intelligent Buildings. Engineering Construction & Design, (06): 20–21 + 27.

[9] Song X, 2024, Research on the Sustainable Development Strategy of Green Construction and Intelligent Buildings. Ceramics, (04): 162–164.

[10] Xiong H, 2024, Application of Green Intelligent Building Information Technology Under the Background of Low-Carbon Economy. Urban Construction Theory Research (Electronic Edition), (09): 205–207.

[11] Han F, 2024, Advantages of Intelligent Building Technology and Its Application in Green Building Construction. Housing and Real Estate, (09): 10–12.

[12] Chen Y, 2024, Research on the Application of Green Energy-Saving Technology in the Intelligent Building Industry. China Strategic Emerging Industry, (09): 128–131.

[13] Bi J, 2024, Application and Optimization of Intelligent Building Technology in Green Construction Projects. Residential Industry, (03): 87–89.

[14] Zheng J, 2023, Analysis on the New Development and Application of Green Intelligent Building Technology. Ceramics, (09): 184–186.

[15] Wang X, Yuan X, Gao D, 2023, Application of BIM Technology in the Structural Design of Green Intelligent Buildings. Foshan Ceramics, 33(07): 57–59.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Application of Self-Healing Concrete in Sustainable Architecture: Mechanisms, Performance, and Future Prospects

Weiye Chen*

Fuzhou University of International Studies and Trade, Fuzhou 350202, Fujian, China

**Author to whom correspondence should be addressed.*

Abstract: The construction industry faces significant challenges due to the inherent brittleness and cracking tendency of traditional concrete, which compromises structural durability and necessitates frequent, costly repairs. This paper explores the groundbreaking development of self-healing concrete as a transformative material technology for sustainable architecture. We examine three primary autogenous healing mechanisms: encapsulated polymer/microbial healing agents, vascular networks, and shape memory alloys. Through a review of recent laboratory experiments and pilot projects, this study analyzes the crack-sealing efficiency, recovery of mechanical properties, and long-term durability of these materials. A comparative case study of a demonstration building facade incorporating microbial self-healing concrete is presented, showing a potential 30% reduction in maintenance costs over a 20-year lifecycle. The findings indicate that self-healing concrete not only enhances structural resilience but also significantly reduces the carbon footprint associated with building maintenance, aligning with the core principles of sustainable development. The paper concludes by discussing current limitations in mass production and cost-effectiveness and proposes directions for future research to facilitate widespread adoption in architectural engineering.

Keywords: Self-healing concrete; Sustainable materials; Biomimicry; Structural durability

Online publication: October 30, 2025

1. Introduction

Concrete stands as the most widely utilized building material across the globe, fundamental to modern infrastructure due to its high compressive strength, durability, and relatively low cost. However, a fundamental and enduring weakness lies in its inherent brittleness and susceptibility to the development of micro-cracks when subjected to tensile, flexural, or shear stresses. These micro-cracks, often invisible to the naked eye, initiate a detrimental cycle of deterioration. They act as permeable pathways for the ingress of aggressive agents such as water, oxygen, chloride ions from deicing salts or marine environments, and carbon dioxide (CO_2). Once inside, these elements trigger a series of destructive processes: chlorides and oxygen corrode the steel reinforcement, causing it to expand and spall the surrounding concrete, while CO_2 carbonates the matrix, lowering its alkalinity and accelerating corrosion. This compromises the structural integrity, reduces the service life, and necessitates frequent and costly interventions [1].

Traditional repair methodologies, such as manual injection of epoxy resins or application of surface coatings, are largely passive and reactive. They are not only invasive and labor-intensive but also often constitute a temporary fix rather than a permanent solution, as they do not address the ongoing phenomenon of new crack formation. Consequently, the lifecycle maintenance costs of concrete structures can become prohibitively high, and the environmental footprint associated with continuous repair work is significant [2].

Inspired by autonomous healing processes found in biological systems—such as the clotting of blood and the regeneration of tissue in human skin—the emerging field of self-healing materials represents a paradigm shift towards intelligent, responsive, and sustainable construction. This paper aims to provide a comprehensive and critical overview of the current state of self-healing concrete technologies. It will meticulously evaluate the various autonomic and vascular healing mechanisms being developed, including but not limited to bacterial-based precipitation of calcium carbonate, microencapsulated healing agents, shape-memory polymers, and vascular networks. The performance of these methods—in terms of crack closure efficiency, durability restoration, mechanical property recovery, and long-term viability—will be systematically analyzed. Furthermore, the paper will discuss the tangible multi-faceted benefits of these technologies, emphasizing their potential to enhance structural resilience, drastically reduce maintenance needs, extend service life, and thereby contribute to the creation of a more sustainable and economically efficient built environment [3].

2. Mechanisms of self-healing

Self-healing concrete represents a revolutionary advance in material science, aiming to endow construction materials with the ability to autonomously repair damage. These mechanisms can be broadly classified into two primary categories: autogenous healing, which is an intrinsic property of traditional concrete, and autonomous healing, which involves the deliberate engineering of additional functional components into the material to provide enhanced self-repair capabilities [4].

2.1. Autogenous healing

Autogenous healing is an inherent, natural process that occurs in standard cementitious materials without any engineered intervention. This mechanism primarily relies on two chemical processes: the continued hydration of unreacted cement particles and the carbonation of calcium hydroxide ($Ca(OH)_2$). When micro-cracks form and water enters the fissures, it reactivates the dormant, unhydrated cement grains present in the matrix. These grains undergo further hydration, forming additional calcium silicate hydrate (C-S-H) gel and other hydration products that can gradually fill and seal the crack. Simultaneously, calcium hydroxide dissolved in the pore solution can migrate to the crack surface, where it reacts with atmospheric carbon dioxide (CO_2) to form calcium carbonate ($CaCO_3$) crystals, which also contribute to sealing the crack. While this process is beneficial and cost-effective as it requires no additional materials, its significant limitations must be acknowledged. Autogenous healing is only effective in sealing very fine cracks, typically those with a width of less than 0.2 to 0.3 millimeters. Furthermore, its efficacy is highly dependent on the availability of water and unhydrated cement, and it cannot repair damage repeatedly or in larger, structurally significant cracks, making it an unreliable standalone solution for long-term durability [5].

2.2. Autonomous healing (engineered)

Autonomous healing mechanisms are the product of advanced material engineering, designed to provide a more robust, reliable, and often repeatable healing response. This approach is the central focus of modern research in self-healing concrete and encompasses several innovative strategies:

Capsule-based healing: This bio-inspired strategy involves the incorporation of microcapsules or macrocapsules made from brittle materials such as glass, ceramic, or polymer directly into the concrete mix during batching. These capsules are meticulously designed to rupture under tensile stress and are filled with a liquid healing agent. Common healing agents include polymers like epoxy or polyurethane resins, which polymerize upon contact with a catalyst (either pre-mixed in the concrete or embedded in separate capsules) or moisture in the crack. In a more complex biological approach, capsules may contain dormant bacterial spores (e.g., *Bacillus sphaericus* or *Bacillus pseudofirmus*) along with an organic calcium nutrient source (e.g., calcium lactate). The major advantage of this system is its localized and rapid response; damage triggers immediate repair at the exact site of cracking. However, a key limitation is that the healing is typically a one-time event, as the capsules are consumed upon rupture [6].

Vascular networks: Mimicking the sophisticated circulatory system found in humans and animals, this method involves embedding a three-dimensional network of hollow tubes or capillaries (made from glass, polymer, or even biodegradable materials) within the concrete structure. These networks can be interconnected and may span the entire structural element. Unlike capsule-based systems, vascular networks can be designed to be recharged. When a crack intersects and breaches one of these tubes, a liquid healing agent stored in an external reservoir can be manually or passively drawn into the crack via capillary action. Some advanced systems even use a pressurized reservoir to actively pump the healing agent into the damaged zone. This design allows for multiple healing cycles throughout the structure's lifespan, addressing a critical drawback of the capsule-based approach. The complexity of installation and the potential for network clogging or damage during construction remain significant engineering challenges [7].

Microbial-induced calcium carbonate precipitation (MICP): This is a highly innovative and sustainable biological strategy that utilizes microorganisms to repair damage. Specifically selected alkali-tolerant, endospore-forming bacteria (such as *Bacillus sphaericus*) and their nutrient source (often an organic calcium compound like calcium lactate) are incorporated into the concrete. To protect the bacteria from the highly alkaline environment and mechanical stress during mixing and hardening, they are first immobilized in porous lightweight aggregates or specially designed capsules. The mechanism is triggered by the ingress of water through a new crack. This water dissolves the nutrients and resuscitates the dormant bacterial spores. The metabolically active bacteria then consume the calcium nutrient, and through their biological processes, they elevate the pH around them and facilitate the precipitation of insoluble, robust calcium carbonate (limestone—$CaCO_3$) crystals. This biomineralization process effectively seals the crack from the inside out, restoring the concrete's integrity and impeding further water penetration. The primary challenges lie in ensuring the long-term viability of the bacteria within the concrete matrix and scaling up the technology for economical industrial application.

3. Performance analysis and experimental evidence

3.1. Laboratory demonstrations of self-healing concrete

A substantial body of rigorous laboratory research has been dedicated to empirically validating the efficacy and superior performance of various self-healing concrete technologies. These investigations are meticulously designed to simulate real-world damage scenarios under controlled conditions, providing critical insights into the healing potential and mechanical restoration capabilities of these advanced materials. Studies commonly employ notched beam bending tests, splitting tensile tests, or controlled compression loading to induce cracks of specific widths in standardized concrete specimens, which are then subjected to optimal healing conditions—typically environments with high humidity or cyclic wet-dry cycles that promote the healing process. The results from these experiments consistently and compellingly demonstrate that self-healing concrete systems can autonomously initiate repair mechanisms upon crack formation, effectively restoring material continuity and significantly recovering mechanical properties without any human intervention. This body of evidence forms a robust foundation for advocating the integration of self-healing technologies into modern construction practices aimed at enhancing durability and sustainability.

3.2. MICP-based concrete performance

Extensive research has been conducted on MICP, a bio-inspired approach that harnesses the metabolic activity of specific alkali-resistant bacteria to precipitate calcite and seal cracks. In these experiments, bacterial spores such as *Bacillus sphaericus* or *Bacillus cohnii*, along with a calcium-based nutrient precursor (e.g., calcium lactate), are incorporated into the concrete matrix, often via protective carriers like lightweight expanded clay aggregates or gelatin microcapsules to ensure survivability. Post-cracking, water infiltration activates the bacterial spores, initiating their metabolic processes. The bacteria consume the organic calcium source, leading to a localized increase in pH and the subsequent deposition of insoluble, robust calcium carbonate ($CaCO_3$) crystals that bridge the crack faces. Quantitative analyses reveal that MICP-treated specimens can recover up to 90% of their original tensile strength and regain a substantial portion of their flexural strength and stiffness. This remarkable recovery is attributed to the effective crack sealing and rebonding of the matrix, which directly translates to enhanced resistance to further degradation, prolonged service life, and reduced permeability, making MICP a highly promising strategy for critical infrastructure exposed to harsh environments.

3.3. Capsule-based healing systems

Capsule-based healing systems represent a prominent autonomous repair strategy where micro- or macro-capsules, fabricated from brittle materials like glass, urea-formaldehyde, or ceramics, are dispersed within the concrete during mixing. These capsules are filled with a liquid healing agent, such as cyanoacrylate, epoxy, or polyurethane-based polymers. When a propagating crack intersects a capsule, the resulting stress concentration causes it to rupture, releasing the healing agent into the crack plane through capillary action. The agent then undergoes polymerization—either upon contact with a catalyst embedded elsewhere in the matrix or with moisture in the air—forming a solid, adhesive plug that seals the crack. Laboratory fatigue and static load tests have demonstrated that this mechanism can effectively autonomously seal cracks up to 0.5 mm in width. Furthermore, advanced systems employing dual-capsule designs (separate containers for resin and hardener) have shown even greater efficiency in achieving complete polymerization. The success of this healing is not only evaluated visually but also through significant reductions in water permeability (often by over 80%) and recovery of mechanical properties, confirming that capsule-based systems can prevent the ingress of deleterious substances like chlorides and sulfates, thereby markedly enhancing the durability and longevity of concrete structures in aggressive environments such as marine settings or highway bridges.

3.4. Quantification of healing efficiency

The performance and efficiency of self-healing concrete are rigorously quantified using a multi-faceted experimental approach, combining mechanical, durability, and microstructural analysis techniques. The most direct metric is the healing ratio, calculated by comparing the recovered mechanical properties (e.g., tensile strength, flexural strength, or stiffness) of healed specimens to their original, undamaged state and to untreated control samples. This is often determined through reloading tests performed after a designated healing period.

Complementing mechanical tests, durability-based assessments are crucial. Water permeability tests, such as the constant head or water flow method, are conducted to measure the rate of water passage through a previously cracked and healed sample. A drastic reduction in permeability indicates successful crack sealing and is a critical indicator for long-term durability, as it directly correlates to the material's ability to resist corrosion-inducing agents.

At the micro-scale, advanced imaging and analytical techniques provide incontrovertible evidence of the healing phenomenon. Scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy is extensively used to visualize the crack morphology and identify the chemical composition of the healing products—confirming, for instance, the presence of calcium carbonate in MICP systems or polymer films in capsule-based systems. X-ray computed tomography offers a non-destructive, three-dimensional view into the internal structure of the crack, allowing researchers to assess the volume and distribution of the healing precipitate within the crack void. This multi-method validation framework is essential for building confidence in the reliability and effectiveness of self-healing concrete.

3.5. Summary of experimental evidence

In summary, the collective experimental evidence from laboratories worldwide provides strong and optimistic support for the viability of self-healing concrete as a transformative technology in construction materials science. Both MICP-based and capsule-based systems, among others, have repeatedly demonstrated a remarkable ability to autonomously repair damage, leading to substantial recovery of mechanical integrity and a dramatic improvement in durability performance by reducing permeability. The consistent success observed under controlled laboratory conditions across these varied healing mechanisms underscores a significant potential to mitigate the pervasive issue of concrete deterioration. The comprehensive quantification strategy—encompassing strength regain, permeability reduction, and microstructural analysis—offers a holistic understanding of healing efficiency and provides a solid scientific basis for transitioning these innovative materials from laboratory research to full-scale field applications and eventual commercialization in real-world construction projects, promising a new era of resilient, sustainable, and low-maintenance infrastructure.

4. Case study: Bio-facade demonstration project

A notable real-world application of innovative self-healing construction materials can be observed in the "Bio-Skin" facade of a prominent research building located in the Netherlands. This project represents a significant advancement in sustainable building technologies. The facade was constructed using pre-cast concrete panels that were specially engineered by incorporating clay pellets infused with bacterial spores and essential nutrients. These embedded bacteria, once activated by the presence of moisture and oxygen, possess the remarkable ability to precipitate calcium carbonate, thereby autonomously sealing microcracks that may form within the concrete structure.

Over a comprehensive monitoring period spanning two years, researchers and engineers closely observed the performance of the Bio-Skin system. During this time, the facade was subjected to natural environmental stresses, such as repeated thermal cycling, which typically causes expansion and contraction in building materials. This process often leads to the formation of hairline cracks in conventional concrete facades. However, in the case of the Bio-Skin panels, these hairline cracks were seen to seal themselves automatically, thanks to the biological activity of the bacteria housed within the clay pellets. This self-healing capability not only preserved the structural integrity and aesthetics of the facade but also minimized the ingress of potentially harmful substances like water and de-icing salts, further enhancing the durability of the construction.

To comprehensively assess the long-term benefits of this innovative facade system, a detailed lifecycle assessment (LCA) model was developed. This model took into account various factors, including the frequency and extent of required maintenance interventions, material longevity, and associated economic and environmental impacts. The results of the LCA were quite promising: projections indicated that the Bio-Skin facade would require 25–30% fewer maintenance interventions throughout its lifecycle compared to a standard concrete facade without self-healing capability. Such a substantial reduction in maintenance not only translates to significant cost savings but also reduces disruptions and resource consumption typically associated with repair work.

Moreover, the environmental benefits of the Bio-Skin system are equally noteworthy. By extending the service life of the facade and lowering the demand for repair materials and activities, the overall carbon footprint and resource usage associated with building maintenance are considerably diminished. This real-world example thus validates both the economic and ecological advantages of integrating self-healing technologies into building envelopes, potentially setting a new standard for sustainable construction practices in the future.

5. Challenges and future outlook

Despite its significant promise, the commercialization of self-healing concrete is currently facing several notable hurdles that need to be addressed before widespread adoption can occur. One of the primary challenges lies in the increased material costs associated with the incorporation of healing agents. Specifically, the addition of these agents, such as encapsulated bacteria or chemical healing compounds, can result in an initial material cost increase ranging from 10% to 50% compared to conventional concrete mixtures. This substantial cost premium poses a barrier, particularly for large-scale construction projects where budget constraints are critical considerations.

Furthermore, there are ongoing concerns regarding the long-term viability and effectiveness of the encapsulated bacteria, which are essential for the self-healing process. Over extended periods, it remains uncertain whether these bacteria can remain dormant yet viable within the concrete matrix, especially when subjected to harsh environmental conditions, repeated mechanical stresses, or chemical exposures. If the bacteria lose their effectiveness before cracks occur, the primary advantage of self-healing concrete may be compromised.

Another area of concern is the potential impact of the healing capsules on the concrete's initial mechanical properties, particularly its compressive strength. The integration of these capsules, while beneficial for promoting self-healing, may inadvertently weaken the concrete's structural performance at early ages. If the initial compressive strength is significantly reduced, the material may fail to meet structural design requirements, compromising the safety, load-bearing capacity, and overall durability of the concrete before the self-healing mechanisms can take effect.

6. Conclusion

Self-healing concrete represents a revolutionary advancement in building materials science, marking a paradigm shift from traditional reactive maintenance to proactive, autonomous repair. By ingeniously mimicking biological repair processes—such as wound healing in living organisms—this innovative material endows concrete structures with the ability to respond to damage internally and spontaneously. This capability promises to significantly enhance the durability, safety, and sustainability of architectural structures. Through the autonomous sealing of micro-cracks, it mitigates the penetration of harmful agents like moisture and chlorides, thereby extending structural service life, reducing maintenance frequency and costs, and minimizing resource consumption over the building's lifecycle.

Although significant challenges in scalability, cost-effectiveness, and long-term reliability under real-world conditions remain, ongoing multidisciplinary research and an increasing number of pilot projects across the globe are steadily paving the way for its integration into mainstream architectural practice. Collaborations between material scientists, structural engineers, and construction industries are crucial in optimizing healing agents, incorporation techniques, and monitoring protocols. As these technologies mature and become more economically viable, self-healing concrete is poised to transition from laboratory innovation to a standard, scalable building solution, ultimately contributing to the vision of resilient, adaptive, and truly "living" buildings that can "heal" themselves.

Disclosure statement

The author declares no conflict of interest.

References

[1] Wang X, Huang Y, Zhang L, 2022, Microencapsulation Technology for Self-Healing Concrete: A Review. Construction and Building Materials, 325: 126667.

[2] Van Tittelboom K, De Belie N, 2013, Self-Healing in Cementitious Materials—A Review. Materials, 6(6): 2182–2217.

[3] Li VC, Herbert E, 2012, Robust Self-Healing Concrete for Sustainable Infrastructure. Journal of Advanced Concrete Technology, 10(6): 207–218.

[4] Wiktor V, Jonkers HM, 2011, Quantification of Crack-Healing in Novel Bacteria-Based Self-Healing Concrete. Cement and Concrete Composites, 33(7): 763–770.

[5] Dry C, 2000, Three Designs for the Internal Release of Sealants, Adhesives, and Waterproofing Chemicals into Concrete to Reduce Permeability. Cement and Concrete Research, 30(12): 1969–1977.

[6] Snoeck D, Van Tittelboom K, Steuperaert S, et al., 2014, Self-Healing Cementitious Materials by the Combination of Microfibres and Superabsorbent Polymers. Journal of Intelligent Material Systems and Structures, 25(1): 13–24.

[7] Wang JY, Soens H, Verstraete W, et al., 2014, Self-Healing Concrete by Use of Microencapsulated Bacterial Spores. Cement and Concrete Research, 56: 139–152.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

A Synergistic Management Framework Integrating Building Information Modeling and Digital Twins in Large-Scale Complex Construction Projects

Longyan Tian*

Fuzhou University of International Studies and Trade, Fuzhou 350202, Fujian, China

**Author to whom correspondence should be addressed.*

Abstract: The management of large-scale architectural engineering projects (e.g., airports, hospitals) is plagued by information silos, cost overruns, and scheduling delays. While building information modeling (BIM) has improved 3D design coordination, its static nature limits its utility in real-time construction management and operational phases. This paper proposes a novel synergistic framework that integrates the static, deep data of BIM with the dynamic, real-time capabilities of digital twin (DT) technology. The framework establishes a closed-loop data flow from design (BIM) to construction (IoT, drones, BIM 360) to operation (DT platform). We detail the technological stack required, including IoT sensors, cloud computing, and AI-driven analytics. The application of this framework is illustrated through a simulated case study of a mega-terminal airport construction project, demonstrating potential reductions in rework by 15%, improvement in labor productivity by 10%, and enhanced predictive maintenance capabilities. This research contributes to the field of construction engineering by providing a practical model for achieving full lifecycle digitalization and intelligent project management.

Keywords: Building information modeling; Digital twin; Construction management; Internet of Things

Online publication: October 30, 2025

1. Introduction

The complexity and scale of contemporary architectural engineering projects have escalated to a degree that traditional management approaches—often reliant on fragmented documentation, two-dimensional drawings, and periodic manual updates—are increasingly inadequate. These conventional methods struggle to ensure the necessary level of coordination, data consistency, and timely communication among the multitude of stakeholders involved—from architects and engineers to contractors and facility managers. In response, building information modeling (BIM) has emerged as a foundational technology, providing a robust platform for three-dimensional visualization, integrated data management, and clash detection during the design and pre-construction phases. By consolidating geometric, semantic, and operational information into a unified digital model, BIM significantly reduces ambiguities and enhances collaborative efficiency.

However, a significant limitation of conventional BIM implementation lies in its static nature; the model is typically updated intermittently rather than in real time, leading to a gradual divergence between the "as-designed" intent and the "as-built" reality over the course of construction. This discrepancy can result in costly rework, delays, and errors during both construction and operation. The emerging concept of the digital twin offers a transformative solution to this challenge. A digital twin is a dynamic, continuously updated virtual replica of a physical asset, synchronizing with its real-world counterpart through a constant flow of data from sensors, drones, and other cyber-physical systems. This paper argues for the integration of BIM as the foundational geometric and informational backbone in the development of a construction digital twin. By uniting the comprehensive detail of BIM with the real-time dynamism of digital twin technology, a powerful synergistic management framework can be established, capable of supporting decision-making, optimizing processes, and enhancing transparency throughout the entire asset lifecycle [1].

2. Theoretical foundation: From BIM to digital twin

2.1. BIM (static digital model)

Building information modeling represents a paradigm shift in architectural and engineering design, moving beyond simple CAD-based drafting to become the central, authoritative information repository for an asset. It encapsulates not only highly detailed, parametric 3D geometry—capturing the exact shapes, dimensions, tolerances, and spatial relationships of every structural, architectural, and MEP (mechanical, electrical, plumbing) component—but also a rich layer of semantic attributes attached to each element. These attributes include material specifications, thermal properties, acoustic performance, fire ratings, maintenance schedules, energy consumption data, manufacturer details, and cost information. This integration of visual and non-visual data within a shared digital environment makes BIM an indispensable tool for visualizing design intent, performing advanced clash detection, improving cost estimation, and facilitating more integrated project delivery.

Nevertheless, the conventional use of BIM is largely static. It serves as a meticulously crafted snapshot of the project at key milestones—such as at the end of each design phase or upon issuance of construction documents. While it can be revised through formalized update cycles, it does not autonomously reflect the ongoing changes, deviations, and construction progress occurring daily on the physical site. This inherent latency means that the BIM model gradually becomes a historical record rather than a live representation. Despite this, its role remains crucial: it acts as the single source of truth that all stakeholders—including architects, structural engineers, contractors, and clients—reference to ensure alignment with the original design intent. Furthermore, BIM's utility extends far beyond construction; it becomes a vital asset for facility management, space planning, renovation projects, and eventual decommissioning, providing a comprehensive digital blueprint that supports the entire lifecycle of the building.

2.2. Digital twin (dynamic virtual entity)

In contrast, a digital twin is a dynamic, living virtual entity that evolves in lockstep with its physical counterpart. It is not merely a model but a connected, interactive simulation that is continuously updated via a bidirectional flow of data. This real-time synchronization is achieved through a dense network of data sources: Internet of Things (IoT) sensors embedded in materials, mounted on equipment, or deployed across the site relentlessly collect data on a vast array of parameters, including temperature, humidity, structural stresses, vibration, energy usage, equipment status, and even worker location and safety compliance. Simultaneously, automated reality capture technologies—such as drones equipped with high-resolution cameras and LiDAR scanners—conduct frequent aerial surveys, generating accurate point clouds and 3D meshes that document daily progress and as-built conditions. Mobile applications further enable field personnel to report progress, log issues, and annotate the digital model directly from the site, incorporating human observation and expertise into the digital record [2].

The true power of the digital twin lies in its analytical and predictive capabilities. By aggregating and processing these voluminous, heterogeneous data streams using advanced artificial intelligence (AI) and machine learning algorithms, the digital twin transforms raw data into actionable insights. It can run simulations, predict potential structural failures or scheduling bottlenecks, optimize resource allocation, and recommend proactive maintenance actions. This enables a shift from reactive decision-making to a predictive and prescriptive approach, where project managers can visualize the consequences of decisions before they are implemented in the physical world. Consequently, the digital twin becomes an indispensable platform for enhancing operational efficiency, ensuring quality control, improving safety management, and reducing environmental impact. It effectively closes the loop between the digital and physical realms, creating a resilient feedback mechanism that allows for continuous learning, optimization, and innovation throughout the construction process and into the entire operational life of the asset.

3. Proposed synergistic management framework

3.1. Physical layer: Smart construction environment

The physical layer constitutes the fundamental level of the integrated BIM-digital twin framework, representing the actual construction site where all tangible operations, material installations, and human activities take place. This environment is systematically transformed into a smart, data-rich ecosystem through the pervasive deployment of an array of advanced sensing and tracking technologies. A diverse suite of IoT sensors is strategically installed across the site to continuously monitor a wide spectrum of environmental and structural parameters—such as temperature fluctuations, humidity levels, vibration, structural deformations, and load stresses—enabling real-time awareness of site conditions and early detection of potential anomalies [3].

Furthermore, critical components, materials, and equipment are tagged with RFID (radio-frequency identification) and barcodes, allowing for seamless tracking from delivery through installation. This provides unparalleled visibility into supply chain logistics, reduces loss or misplacement of assets, and ensures that materials are utilized as planned. Autonomous drones and robotic devices perform regular aerial surveys and terrestrial scans, employing photogrammetry and LiDAR technologies to generate high-resolution, georeferenced 3D maps of the construction progress. These maps are essential for verifying dimensional accuracy and tracking daily changes.

By integrating these technologies, the physical layer functions as a pervasive data generation node, producing a continuous, multi-modal stream of information that reflects the real-time status of the construction process. This digitized jobsite ensures full traceability of operations, enhances safety through constant monitoring, and establishes a reliable and granular data foundation essential for higher-level analytical processing and virtual synchronization.

3.2. Data transmission layer: Cloud-based data processing and integration

Serving as the critical conduit between the physical jobsite and the digital management platforms, the data transmission layer handles the aggregation, harmonization, and secure movement of vast and heterogeneous datasets. Cloud-based integration platforms—such as Autodesk BIM 360, Microsoft Azure, and Amazon Web Services (AWS)—are employed as the central nervous system of the framework. These scalable cloud environments receive raw data in real time from numerous edge devices: environmental sensors, RFID readers, drone-captured imagery, geographic information systems (GIS), and even mobile inputs from field engineers and supervisors.

Upon ingestion, this data undergoes rigorous processing via dedicated data pipelines. Automated ETL (extract, transform, load) procedures cleanse the data, remove noise, and standardize formats to ensure consistency and interoperability. Middleware solutions facilitate the mapping of incoming data streams to corresponding elements within the BIM model, enriching semantic attributes with real-time status updates. The cloud layer also incorporates robust data governance and security mechanisms—including encryption, access controls, and audit trails—to protect sensitive project information and ensure compliance with industry regulations [4].

By offering virtually unlimited storage and computational power, the cloud infrastructure enables complex data correlations and supports real-time analytics without latency bottlenecks. It ensures that all project stakeholders—whether in the office or on site—have secure, role-based access to the most current project information, thereby breaking down information silos and establishing a unified data environment that is essential for collaborative and informed decision-making.

3.3. Virtual layer: Dynamic digital twin for intelligent project management

At the apex of the framework resides the virtual layer, where an intelligent, adaptive, and data-driven digital twin serves as the central command center for project-wide management and simulation. This layer is built upon the detailed BIM model, which acts as the geometric and informational backbone, but transcends its static nature through continuous, bidirectional synchronization with live site data.

The digital twin platform integrates 4D BIM (time-based scheduling) and 5D BIM (cost integration) capabilities, enabling real-time progress monitoring by automatically aligning planned tasks and timelines with actual site advancements. Through sophisticated visualization dashboards and automated deviation alerts, project managers can instantly identify delays, spatial conflicts, or sequencing issues, allowing for swift corrective actions.

Leveraging artificial intelligence and predictive analytics, the digital twin simulates future scenarios based on current trends, historical data, and predefined rulesets. It can forecast potential risks such as resource shortages, safety incidents, or budget overruns, providing stakeholders with actionable insights to mitigate disruptions. Additionally, the system supports real-time resource and logistics optimization by tracking the movement and utilization of labor, machinery, and materials, ensuring that assets are deployed efficiently and idle time is minimized [5].

Acting as a collaborative single source of truth, the digital twin enhances transparency and trust among all parties—owners, designers, general contractors, and subcontractors. It enables immersive design reviews, clash detection in context, and operational readiness testing long before physical execution. By maintaining an ever-accurate virtual replica of the asset, this layer not only drives efficiency and reduces waste during construction but also delivers a comprehensively documented and easily operable digital asset to owners for the entire lifecycle of the facility.

4. Case study simulation: Mega-airport terminal construction

A comprehensive simulation of the digital construction framework was executed for a large-scale airport terminal project. This case study highlights how the integration of advanced digital technologies—such as IoT sensors, drones, BIM, and digital twin platforms—transformed traditional project management and site safety practices. The following key outcomes exemplify the benefits realized during the simulation.

4.1. Clash resolution

In the dynamic and complex environment of airport terminal construction, spatial clashes between equipment and installed systems can result in costly rework and project delays. In this simulation, IoT sensors were installed on the hooks of tower cranes to monitor their movement in real time. During a routine lifting operation, these sensors detected that the crane's hook was on a collision course with a pre-installed HVAC duct. Instantly, this data was relayed to the project's digital twin platform, which processed the information and generated a visual warning in the virtual environment. Simultaneously, the crane operator received an immediate alert through the digital twin interface, enabling them to halt the operation before any damage occurred. By proactively identifying and resolving the impending clash, the system averted potential rework, material waste, and schedule disruptions, demonstrating the value of real-time, sensor-driven spatial awareness [6].

4.2. Progress tracking

To ensure the timely completion of structural steel erection, daily drone flights were programmed to capture high-resolution images and generate detailed point clouds of the construction site. These point clouds were automatically uploaded to the digital twin, which compared them with the planned BIM model to assess progress. Through this automated analysis, the system detected a 2-day delay in the erection process within a specific zone of the terminal. This early identification allowed project managers to respond swiftly, reallocating labor and equipment resources to the affected area to mitigate further delays. The use of drones and automated digital twin-BIM comparisons not only improved schedule transparency but also provided managers with actionable insights, supporting proactive decision-making and efficient resource management throughout the construction phase.

4.3. Safety monitoring

Worker safety is paramount on large construction sites where heavy equipment operates in close proximity to personnel. In the simulated environment, construction workers were equipped with wearable sensors capable of monitoring their locations and movements. These sensors continuously communicated with the digital twin, which tracked the real-time proximity between workers and hazardous equipment, such as cranes and excavators. Whenever a worker approached a predetermined safety threshold near heavy machinery, the digital twin automatically triggered alerts within the virtual environment and activated on-site alarms. This immediate feedback mechanism enabled workers and equipment operators to react swiftly, thus preventing potential accidents. By leveraging wearable technology and the situational awareness provided by the digital twin, the project significantly enhanced on-site safety and fostered a culture of risk prevention [7].

In summary, the simulation of the digital framework in the mega-airport terminal construction project showcased how the integration of IoT, drones, BIM, and digital twin technology can revolutionize construction management. Real-time clash detection, automated progress tracking, and proactive safety monitoring collectively contributed to improved efficiency, reduced risk, and increased project predictability, setting a new standard for smart construction practices in large-scale infrastructure projects.

5. Discussion: Benefits and implementation challenges

The integration of BIM with digital twin technology offers transformative benefits for the architecture, engineering, and construction (AEC) industry. One of the most significant advantages is the enhancement of decision-making processes throughout the project lifecycle. By utilizing a dynamic digital representation of the physical asset, stakeholders gain access to real-time data and simulations, enabling more informed and agile choices. This leads to not only better design and construction outcomes but also long-term operational efficiencies.

Additionally, the implementation of this integrated framework drastically reduces the number of requests for information (RFIs). By maintaining a centralized and constantly updated digital model, potential conflicts and ambiguities are identified and resolved during the design and pre-construction phases, minimizing delays and costly on-site modifications. This proactive approach enhances collaboration among multidisciplinary teams and promotes a more streamlined workflow.

Quality control is substantially improved through continuous monitoring and validation against the digital twin. Sensors, IoT devices, and automated compliance checks allow for real-time comparison between the as-designed and as-built states, ensuring that construction conforms to specifications and standards. This results in fewer defects, reduced rework, and higher overall project quality.

Furthermore, the handover process becomes seamless with the delivery of a high-fidelity "as-built" digital twin to the facility operator. This digital asset serves as a foundational tool for facility management, supporting operations, maintenance, and future renovations. It provides an accurate, up-to-date repository of asset information that improves lifecycle management and operational transparency.

However, the adoption of this advanced framework is not without challenges. A major barrier is the high initial investment required for technology acquisition, software integration, and specialized training. Organizations must allocate significant resources to build the necessary infrastructure and develop in-house expertise, which can be prohibitive for some firms, especially smaller enterprises.

Another critical challenge is the need for robust data standardization and interoperability. To ensure that information flows seamlessly across different platforms and stakeholders, widely accepted standards such as Industry Foundation Classes (IFC) and Construction Operations Building Information Exchange (COBie) must be rigorously implemented. Without consistent data protocols, the potential of BIM and digital twin integration cannot be fully realized.

Cultural resistance also presents a substantial hurdle. The shift from traditional workflows to data-driven, collaborative processes requires changes in mindset and practice. Stakeholders may be reluctant to adopt new technologies or may lack the digital literacy needed to engage effectively with the integrated system. Therefore, change management and continuous training are essential to foster acceptance and maximize the technology's benefits [8].

6. Conclusion

The convergence of BIM and digital twin technology marks a revolutionary advancement in architectural engineering and construction management. This integration signifies a shift from static, fragmented models toward dynamic, intelligent, and predictive project delivery systems. The proposed framework enables a closed-loop feedback mechanism between the digital and physical environments, creating a continuous cycle of data collection, analysis, and optimization.

By bridging the gap between design, construction, and operational phases, this approach greatly enhances the efficiency, safety, and sustainability of large-scale construction projects. It supports not only improved project outcomes but also offers long-term economic and environmental benefits through optimized resource use and extended asset lifespan.

The adoption of such an integrated system sets a new benchmark for the industry, promoting a culture of innovation, transparency, and collaboration. While challenges related to cost, data interoperability, and cultural adaptation remain, the potential returns—ranging from reduced operational costs to enhanced project resilience—make a compelling case for investment.

In conclusion, the fusion of BIM and digital twin technologies is poised to redefine best practices in the built environment. It provides a foundation for smarter infrastructure development and management, paving the way for a more agile and responsive industry capable of meeting the complex demands of the future.

Disclosure statement

The author declares no conflict of interest.

References

[1] Lu Q, Xie X, Heaton J, et al., 2020, From BIM Towards Digital Twin: Strategy and Future Development for Smart Asset Management, in Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing, Springer, Cham, 392–404.

[2] Boje C, Guerriero A, Kubicki S, et al., 2020, Towards a Semantic Construction Digital Twin: Directions for Future Research. Automation in Construction, 114: 103179.

[3] Opoku DGJ, Perera S, Osei-Kyei R, et al., 2021, Digital Twin Application in the Construction Industry: A Literature Review. Journal of Building Engineering, 40: 102726.

[4] Sacks R, Brilakis I, Pikas E, et al., 2020, Construction with Digital Twin Information Systems. Data-Centric Engineering, 1: e14.

[5] Liu Z, Osmani M, Demian P, 2021, Blockchain and BIM Integration for Transparent and Trustworthy Data Management in Construction Projects. Automation in Construction, 132: 103939.

[6] Pan Y, Zhang L, 2021, A BIM-Data Mining Integrated Digital Twin Framework for Advanced Project Management. Automation in Construction, 124: 103564.

[7] Deng M, Menassa CC, Kamat VR, 2021, From BIM to Digital Twins: A Systematic Review of the Evolution of Intelligent Building Representations in the AEC-FM Industry. Journal of Information Technology in Construction (ITcon), 26(5): 58–83.

[8] Kaewunruen S, Rungskunroch P, Welsh J, 2020, A Digital Twin for Evaluating the Vibration and Noise of Railway Stations. Applied Sciences, 10(11): 3877.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on the Design and Structural Performance of Customized Building Components Based on 3D Printing Technology

Zijiang Huang*

Fuzhou University of International Studies and Trade, Fuzhou 350202, Fujian, China

**Author to whom correspondence should be addressed.*

Abstract: Additive manufacturing, commonly known as 3D printing, is transitioning from prototyping to a viable construction technology, enabling unprecedented geometric freedom and material efficiency. This paper focuses on the design, manufacturing, and structural performance of customized, non-standard building components fabricated through concrete 3D printing. It investigates the interplay between computational design tools (e.g., topology optimization, generative design) and the constraints and opportunities of the extrusion-based 3D printing process. The mechanical properties of printed concrete, particularly the anisotropic behavior due to layer-by-layer deposition, are critically analyzed. A series of mechanical tests on printed specimens (compression, flexural, and inter-layer shear) is presented and compared with cast-in-place concrete. The research demonstrates that through intelligent design that aligns with the printing path and material properties, 3D printed components can achieve superior strength-to-weight ratios and novel functional integration (e.g., internal cooling channels). This work provides valuable insights for architects and engineers seeking to leverage 3D printing for creating high-performance, architecturally expressive building elements.

Keywords: 3D concrete printing; Additive manufacturing; Topology optimization; Structural performance

Online publication: October 30, 2025

1. Introduction

The relentless pursuit of architectural innovation and expression frequently gravitates towards complex, non-repetitive, and organic geometries. These forms, while aesthetically compelling and often structurally efficient, have historically been economically unfeasible to construct using traditional formwork-based techniques. The fabrication of custom molds for such unique shapes is prohibitively expensive and time-consuming, rendering most ambitious designs impractical. 3D concrete printing (3DCP) emerges as a profoundly disruptive solution to this long-standing impediment, offering a paradigm shift by building structures layer-by-layer directly from a digital model. This additive approach fundamentally eliminates the need for expensive molds, drastically reduces material waste through precise deposition, and unlocks the potential for mass customization at an unprecedented scale. However, this newfound freedom introduces a significant engineering challenge. This paper delves into the core imperative of 3DCP: ensuring that the aesthetically driven, computationally optimized geometries are also structurally sound, reliable, and capable of meeting stringent performance requirements. We aim to bridge the critical gap between computational design, which explores the realm of the possible, and structural engineering, which governs the realm of the safe and feasible, all within the transformative context of additive manufacturing for construction.

2. Computational design for additive manufacturing

Designing effectively for 3DCP necessitates not merely the adoption of a new set of digital tools, but a complete and fundamental rethinking of conventional architectural and structural design paradigms. Traditional methods are inherently constrained by the limitations of formwork, the economics of standardized shapes, and established construction practices, which collectively stifle innovation and limit the freedom to exploit the unique capabilities of additive manufacturing. In stark contrast, design for additive manufacturing (DfAM) proactively leverages the flexibility of 3D printing to realize geometrically complex, functionally graded, and highly efficient forms and structures that were previously considered unbuildable or economically non-viable.

A central and powerful component of DfAM is topology optimization (TO), a computational physics-based approach that systematically determines the most efficient material distribution within a predefined design space, subject to specific loading conditions, boundary conditions, and performance constraints. TO algorithms, such as the solid isotropic material with penalization (SIMP) method or evolutionary structural optimization techniques, work iteratively to remove material from regions experiencing low stress while retaining and reinforcing material along critical high-stress paths. The outcome is often an organic, bone-like, or lattice-like geometry that maximizes structural efficiency (stiffness-to-weight ratio) and minimizes material usage, thereby promoting sustainability.

However, these structurally optimal geometries are often highly complex, featuring intricate internal voids, branching structures, and significant overhangs that cannot be fabricated using traditional subtractive or formative methods. They are, nevertheless, ideally suited for the layer-by-layer additive construction inherent to 3D printing. To bridge the gap between theoretical optimization and practical printability, generative design tools are employed. These tools allow designers to input a set of print-process-specific constraints, such as minimum printable feature size, maximum allowable overhang angles (to prevent collapse during printing without supports), and the desired orientation of print layers for optimal mechanical performance. The generative algorithms then iteratively adjust and refine the topology to avoid manufacturing failures, reduce the need for temporary support material, and ensure the continuous, uninterrupted flow of concrete extrusion.

Furthermore, toolpath optimization constitutes an essential and often overlooked step in the DfAM process for 3DCP. The printing path is no longer merely a trajectory to fill a shape; it is algorithmically generated to not only accurately reproduce the optimized geometry but also to actively enhance the mechanical performance of the printed part. For instance, by strategically aligning the extrusion direction with the principal stress trajectories identified through finite element analysis, the resulting component can achieve a higher load-bearing capacity and improved durability, effectively tailoring the material's inherent anisotropy to its structural purpose. These integrated computational strategies—topology optimization, generative design, and toolpath planning—collectively enable the creation of highly efficient, structurally sound, and materially optimized components that fully exploit the disruptive potential of additive manufacturing in construction.

3. Material characteristics and anisotropic behavior

The extrusion-based 3D concrete printing process imposes unique and pronounced characteristics on the resulting material, the most significant of which is pronounced anisotropy in its mechanical properties. This stands in sharp contrast to traditionally cast concrete, which, if properly vibrated and cured, can generally be assumed to exhibit isotropic behavior owing to its uniform compaction and monolithic hydration process. 3D-printed concrete, however, is built up in discrete layers. The interface between these successive layers, formed as each new layer is extruded onto a previously deposited one that has already begun setting, introduces inherent potential weaknesses due to the so-called "cold joint" phenomenon. This is where fresh material bonds imperfectly to a partially set or hardened material, creating a plane of weakness. This layered architecture results in significantly higher mechanical strength along the plane of the layers (the parallel direction) compared to the direction perpendicular to the layers (the inter-layer direction).

A multitude of interrelated factors contribute to the degree of this anisotropy. The rheological properties of the concrete mix are paramount: its yield stress and viscosity must ensure it holds its shape immediately after extrusion while remaining sufficiently workable to bond with the next layer. The contact surface area between layers can be imperfect, potentially leaving behind microscopic voids, pores, or poorly bonded interfaces. The time gap between subsequent layer depositions (layer interval time) is critical; too long a gap reduces moisture content and hydration potential at the interface, weakening the bond. Environmental conditions, such as ambient temperature and humidity, further influence the rate of setting and evaporation, thereby impacting bond quality. Consequently, the compressive, tensile, and flexural strengths measured perpendicular to the print layers are often substantially lower—typically in the range of 20–40%—than those measured parallel to the layers.

To address these critical challenges, extensive research has focused on multi-faceted optimization of the concrete mix design specifically for 3D printing. Enhancing thixotropy—the ability of the mix to exhibit low viscosity and high fluidity during extrusion (under shear stress) but rapidly regain a high yield stress and stiffen to support subsequent layers immediately upon resting—is considered a key objective. Chemical admixtures play a crucial role: superplasticizers improve flowability and reduce yield stress for pumping without increasing water content, which is essential for maintaining ultimate strength, while viscosity-modifying agents enhance green strength and shape stability. Set accelerators can be used to ensure rapid stiffening, improving buildability. Furthermore, the inclusion of micro-fibers, such as polypropylene or steel fibers, helps bridge micro-cracks and the inter-layer interface, increasing tensile strength, ductility, and reducing the likelihood of plastic shrinkage cracks. Research into chemical admixtures that promote secondary hydration or crystalline growth across the interface is also ongoing to enhance chemical bonding and improve overall structural integrity.

In summary, understanding, characterizing, and mitigating anisotropic behavior is absolutely critical for predicting structural performance and ensuring the long-term reliability and safety of 3D-printed concrete structures. Ongoing research into advanced mix designs, real-time process control, and potential post-processing treatments continues to push the boundaries of performance and scalability for extrusion-based additive manufacturing in construction.

4. Experimental methodology and results

4.1. Materials development

The comprehensive experimental program commenced with the meticulous formulation and development of a high-performance, fine-grained concrete mix specifically engineered for extrusion-based 3D printing. The mix design process involved an iterative, empirical testing protocol to achieve optimal and balanced rheological properties, focusing on the critical triad of pumpability (ease of transportation), extrudability (ease of deposition through a nozzle), and buildability (ability to support weight without deformation). A Portland cement-based binder system with carefully selected supplementary cementitious materials (like silica fume or fly ash) was used to enhance cohesiveness and final density. High-range water-reducing superplasticizers were incorporated at an optimal dosage to significantly enhance the flow characteristics of the concrete without increasing the water-to-binder ratio, which is paramount for achieving high mechanical strength. Polypropylene fibers, 6–12 mm in length, were added to the mix at carefully controlled dosages (typically 0.1–0.5% by volume); these fibers serve primarily to inhibit plastic and hardened state crack propagation, increase ductility post-cracking, and improve the cohesion and green strength of the freshly extruded filaments. Additional specialized admixtures, such as viscosity-modifying agents to prevent segregation and ensure stability, and set accelerators to control the stiffening rate and ensure rapid gain of early strength, were judiciously used to guarantee that each layer would stiffen rapidly enough to support the weight of subsequent layers without significant deformation or collapse [1].

4.2. Printing procedure

All test specimens were printed using a robust three-axis gantry-style 3D printer equipped with a progressive cavity pump for consistent material flow and capable of precise digital control over all critical extrusion parameters. The key process variables systematically investigated included layer height (e.g., 10–20 mm), nozzle travel speed (e.g., 50–100 mm/s), and extrusion rate (calibrated to match travel speed and achieve a continuous filament). By methodically varying these parameters according to a designed experimental plan, the research aimed to quantitatively assess their individual and interactive impact on both print quality (e.g., dimensional accuracy, surface finish, filament uniformity) and the resulting mechanical properties of the hardened concrete. The printed specimens included standard 100 mm cubes for compressive strength tests and 40×40×160 mm prisms for flexural tests. Critically, each specimen type was printed in two distinct orientations relative to the printing bed: one with the loading direction parallel to the printed layers and another with the loading direction perpendicular to the layers. This strategic orientation allowed for a direct and clear evaluation of the material's anisotropic behavior. All printing operations were conducted in a controlled laboratory environment with stable temperature and humidity to minimize variability due to fluctuating ambient conditions.

4.3. Mechanical testing

After a standard 28-day curing period under controlled laboratory conditions (wrapped in plastic to prevent moisture loss), the printed specimens were subjected to a comprehensive series of destructive mechanical tests. Uniaxial compression tests were performed using a servo-controlled universal testing machine, with specimens loaded both parallel to and perpendicular to the print layers to directly quantify anisotropy. Flexural strength (modulus of rupture) tests were conducted using a standard three-point bending setup on the prism specimens. To provide a rigorous benchmark and isolate the effect of the printing process itself, identical specimens were fabricated by traditional casting in steel molds, using the exact same batch of concrete mix. This provided a direct and meaningful comparison between the properties of conventionally cast concrete and 3D-printed concrete, under otherwise identical material conditions [2].

4.4. Results and analysis

The test results unequivocally confirmed the theoretically anticipated and pronounced anisotropic behavior in the printed specimens. Compressive strength measured in the direction perpendicular to the print layers was consistently found to be 20–30% lower than the strength measured parallel to the layers. However, the use of the optimized fiber-reinforced mix design, combined with careful calibration and control of printing parameters (notably a minimal time gap between layers and optimal nozzle standoff distance), led to a significant improvement in inter-layer bond strength compared to values often reported in earlier literature. Notably, the inter-layer (perpendicular) compressive strength reached up to 85% of that measured for the traditionally cast concrete, indicating substantial progress in mitigating the weaknesses typically associated with the layered extrusion process. Flexural tests exhibited a similar trend, with the parallel-oriented specimens outperforming the perpendicular ones. The inclusion of polypropylene fibers effectively enhanced the overall ductility and toughness in both directions, transforming the brittle failure mode of plain concrete into a more gradual, pseudo-ductile failure with multiple micro-cracks [3].

These findings powerfully underscore the inextricable link and critical importance of both advanced material science (mix design) and precise process control (printing parameters) in achieving high-quality, structurally reliable 3D-printed concrete. The results suggest that, with continued refinement and standardization, extrusion-based 3DCP can reliably produce structural components with mechanical properties approaching those of conventionally cast concrete, while simultaneously offering the unparalleled added benefits of geometric freedom, digital integration, and material efficiency.

5. Case study: Topology-optimized structural node

To demonstrate the practical integration of these computational and material advancements, a specific case study was conducted on the design, optimization, and fabrication of a critical structural node for a complex space frame structure. Traditionally, such nodes are heavy, often over-engineered solid elements, designed conservatively to accommodate multiple intersecting members and transfer complex loads efficiently. However, through the application of advanced computational design techniques tailored for additive manufacturing, a radically different, lightweight, and high-performance approach was implemented [4].

The process began with a thorough structural analysis to define the node's functional requirements, including the precise magnitude and direction of all expected loads from the connecting members and the spatial constraints of their arrangement. Using density-based topology optimization (SIMP method) within the defined design space and under these constraints, material was iteratively removed from regions experiencing minimal stress. This process resulted in a highly efficient, organic, and intricate geometry that closely follows the natural load paths, effectively creating a strut-and-node system within a single component. This optimization not only reduced the weight of the node by approximately 40% compared to a conventional prismatic design but also created an aesthetically distinctive form that would be virtually impossible to fabricate accurately using any subtractive or formative manufacturing methods [5].

To ensure practical printability, the generative design process incorporated specific constraints related to the 3D printing process. These included defining a maximum allowable overhang angle (e.g., 45 degrees) to avoid the need for support structures, establishing a minimum printable wall thickness, and defining a favorable print orientation. The final optimized geometry was then subjected to automated toolpath generation. Critically, the extrusion paths were strategically aligned with the principal stress trajectories previously identified in a detailed finite element analysis (FEA). This deliberate alignment maximized the mechanical performance of the node, as the printed layers—and the inherent strength direction—were oriented to best resist the predominant applied loads, turning material anisotropy into a design advantage.

The as-designed node was subsequently evaluated using high-fidelity structural FEA simulations, which confirmed that, despite the substantial weight reduction, the component could safely withstand all design loads with a comfortable safety factor. This case study not only exemplifies the power of integrating computational design (TO, generative design) with additive manufacturing for producing high-performance, lightweight structural components but also tangibly highlights the significant potential for material savings, reduced embodied energy, and waste reduction in construction through the adoption of these synergistic technologies [6].

6. Challenges and future directions

Despite the significant advances demonstrated in both research and pioneering projects, several critical and interconnected challenges remain to be addressed before 3D concrete printing can achieve widespread, code-governed adoption in the mainstream construction industry. One major hurdle is the current lack of standardized testing, qualification, and certification protocols specifically developed for 3D-printed structures. Unlike conventional construction materials (e.g., cast-in-place concrete, steel rebar), which are governed by well-established international codes and standards, the unique properties of printed materials—especially their pronounced anisotropic behavior, dependency on process parameters, and potential for localized defects—necessitate the development of entirely new evaluation criteria, safety factors, and performance-based design guidelines.

Another significant challenge lies in scaling up the technology for robust, large-scale, and cost-effective real-world applications. While small-scale elements, architectural features, and proof-of-concept prototypes have been successfully printed, the transition to load-bearing, full-scale structural components like walls and columns requires continued improvements in printer scalability, reliability, automation, and the logistics of continuous material delivery on busy job sites. Furthermore, the integration of reinforcement remains a primary focus. The automated placement of continuous steel rebar, the embedding of pre-tensioned cables, or the development of novel reinforcement strategies (e.g., robotic welding of in-process wire mesh, use of high-strength fiber reinforcement) are active and critical areas of research essential for realizing the full structural potential of 3D-printed concrete, particularly in seismic zones [7].

Looking ahead, future research directions are expansive and interdisciplinary. They include the development of multi-material and functionally graded printing technologies, allowing for the strategic distribution of different materials within a single component to achieve optimal performance characteristics (e.g., high strength in one area, high insulation in another). The integration of smart materials—capable of sensing strain (self-sensing), self-healing micro-cracks, or adapting to changing environmental conditions—offers exciting possibilities for the next generation of intelligent, durable, and responsive structures. Additionally, advances in real-time process monitoring (e.g., computer vision for layer inspection, ultrasonic testing for bond quality) coupled with closed-loop control systems will be crucial for enhancing reliability, ensuring quality assurance, and unlocking the full creative potential of additive manufacturing in construction [8].

7. Conclusion

3D concrete printing technology fundamentally unlocks a new realm of possibilities for architectural expression, structural performance, and material sustainability. This research has demonstrated that moving beyond the limitations of traditional construction requires an integrated methodology where design is intrinsically linked to the manufacturing process and a deep understanding of material science. By leveraging computational tools like topology optimization and generative design, architects and engineers can co-create components that are not only visually striking and geometrically complex but also structurally efficient, materially economical, and environmentally conscious. This study specifically underscored the critical importance of understanding, characterizing, and designing for material anisotropy inherent in the layer-by-layer process. It has been shown that through sophisticated mix design incorporating fibers and admixtures, along with precise control of printing parameters, the mechanical performance of printed concrete can approach that of traditional concrete. By embracing this holistic approach, the industry can harness the full potential of 3D printing to revolutionize architectural engineering, paving the way for a future built environment that is lighter, stronger, more resource-efficient, and more responsive to the multifaceted needs of modern society.

Disclosure statement

The author declares no conflict of interest.

References

[1] Buswell RA, Leal de Silva WR, Jones SZ, et al., 2018, 3D Printing Using Concrete Extrusion: A Roadmap for Research. Cement and Concrete Research, 112: 37–49.

[2] Wang L, Ma G, Li Z, 2021, Anisotropic Behavior in 3D Printed Concrete: A Review. Additive Manufacturing, 47: 102328.

[3] Gosselin C, Duballet R, Roux P, et al., 2016, Large-Scale 3D Printing of Ultra-High Performance Concrete—A New Processing Route for Architects and Builders. Materials & Design, 100: 102–109.

[4] Le TT, Austin SA, Lim S, et al., 2012, Hardened Properties of High-Performance Printing Concrete. Cement and Concrete Research, 42(3): 558–566.

[5] Xia M, Sanjayan J, 2016, Method of Formulating Geopolymer for 3D Printing for Construction Applications. Materials & Design, 110: 382–390.

[6] Wu P, Wang J, Wang X, 2016, A Critical Review of the Use of 3D Printing in the Construction Industry. Automation in Construction, 68: 21–31.

[7] Nerella VN, Hempel S, Mechtcherine V, 2019, Effects of Layer-Interface Properties on Mechanical Performance of Concrete Elements Produced by Extrusion-Based 3D-Printing. Construction and Building Materials, 205: 586–601.

[8] Lim S, Buswell RA, Le TT, et al., 2012, Development of a Viable Concrete Printing Process, Proceedings of the 28th International Symposium on Automation and Robotics in Construction (ISARC 2012), 665–670.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

A Dialogue Between a New Building and the Existing Historical Environment: A Case Study of the Residential Building at the Historic Heart of Tel Aviv

Nili Portugali*

23 Ben-Yosef St. Tel Aviv, 6912523, Israel

***Corresponding author:** Nili Portugali, nili_p@netvision.net.il

Abstract: Preserving the spirit of a historical environment does not necessarily mean a repetition of its language generated by nostalgia. The aim of this article is to present the way I was trying to form a real dialogue between a new modern residential building and the existing historic urban district of the city of Tel Aviv, neither by reconstructing the past nor dissociating from it by enforcing a completely new order. A district that already provided a unique interface between Eastern and Western architecture, being a micro-document of the architectural history of Tel Aviv from 1920 to 1930.

Keywords: Holistic; Architecture; Organic; Residential building; Conservation

Online publication: October 31, 2025

1. Introduction: Architecture is made for people

The holistic-phenomenological worldview in theory and in practice has stood in recent years at the forefront of the scientific discourse in disciplines like cosmology, neurobiology, psychology, particle physics, brain sciences, recent theories of complexity, as well as being in convergence with the fundamentals of Buddhist philosophy that my work is associated with [1]. The purpose of architecture, as I see it, is first and foremost to create a human environment for human beings. Yet, modern society has lost the value of man and thus created a feeling of alienation between man and the environment. Buildings affect our lives and the fate of the physical environment in which we live over the course of many years; therefore, their real test is the test of time. The great buildings, villages, and temples in which man feels "at home"—the ones we want to return to again and again and thus have timeless relevance—are the ones that touch our hearts and have the power to create a deep emotional experience (**Figure 1**).

Figure 1. Villages that evoke a deep sense of belonging, The Island of Paros, Greece

An apartment building is much beyond a shelter. As opposed to the common apartment buildings being built today being "copy and paste models," which normally create an anonymous and uniform environment, a fundamentally different approach was adopted here. The intention was first to create a place where the tenants will really feel at home and a sense of belonging, from the moment they enter the site until they reach their private apartment (**Figure 2**).

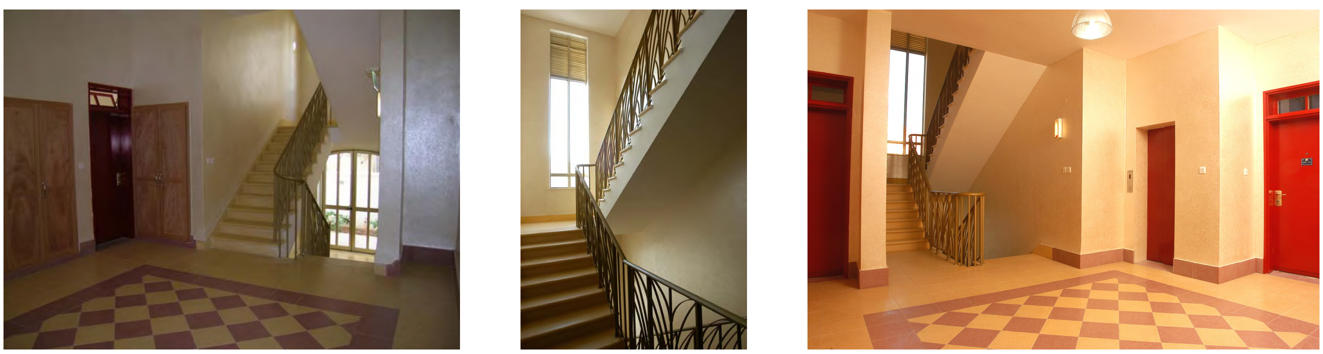


Figure 2. The Residential building, Tel Aviv, designed by Nili Portugali

Secondly, to create a building that will contribute significantly to the public space, the street whose boundaries it defines (**Figure 3**).

Figure 3. The Residential building, Tel Aviv, designed by Nili Portugali

As in any organic system, each building has its own uniqueness and power; at the same time, it always functions as part of a larger environment for which its existence and wholeness it is responsible [2].

There are different ways to describe buildings that have this timeless quality, buildings that convey an inherent spiritual experience. Frank Lloyd Wright called them "the ones which take you beyond words."

Quoted Christopher Alexander by Stephen Grabow in his book [3]: "*The buildings that have spiritual value are a diagram of the inner universe or the picture of the inner soul.*"

Although this timeless quality exists in buildings rooted in different cultures and traditions (**Figure 4**), the emotional experience they generate is common to all people, no matter where or from what culture they come from.

Figure 4. Left to right: Tholos, 4th century, Delphi, Greece; Great Gander Pagoda, 7th–8th century, Hsi-an-Fu, China; Abuhab Synagogue, Safed, Israel

Thus, Christopher Alexander's basic assumption was that behind human architecture there are universal codes, and that beauty and harmony in architecture and in man-made works of art are objective properties inherent within the structure itself [4,5], reflecting the "innate patterns" (used by Noam Chomsky's terminology in reference to the spoken language) that are already structured in our mind from the outset, thus common to us all as human beings.

Contemporary architecture and art sought to dissociate itself from the world of emotions and connect the design process to the world of ideas, thus creating a rational (intellectual) relation between building and man, devoid of any emotion. The basic argument presented here is that in order to change the feeling of the environment and create places and buildings we really feel "at home," what is needed is not a change of style or fashion, but a transformation of the mechanistic worldview underlying current thought and approaches to the holistic one.

2. Between two worldviews: The holistic approach vs the mechanistic approach

The difference between the worldview that resulted in dissociating man from his environment and the worldview that considers man to be part of the physical world he lives in (as well as part of nature) emphasizes the difference between the holistic organic school of thought to which my own work belongs and the mechanistic-fragmentary worldview. These are two different sets of orders [2].

The mechanistic worldview, which has long dominated Western thought and underpins much of contemporary architecture, promotes a separation of elements, leading to environments composed of autonomous and mechanically ordered fragments. This fragmented approach is evident in urban developments such as Brasília in Brazil, Chandigarh in India, and the satellite towns of England. In these settings, the structured disconnection between the house and the street, the street and the neighborhood, and the neighborhood and the city contributes to a pervasive sense of detachment and alienation.

The house appears to be a random collection of objects; the street appears to be a random collection (catalogue) of buildings that do not form together a street (often even prefabricated, transported units made in a factory and superimposed on the site); the streets do not form together a neighborhood; and the neighborhoods do not create a city.

In contrast to these fragmented developments are buildings designed by those who recognized that architectural responsibility lies first and foremost in shaping the quality of the street, whose boundaries the buildings help define. These designers understood that urban design does not begin and end with arbitrary sketches drawn at a scale of 1:1000, but rather with a continual sensitivity to the scale of the human experience—the scale of 1:1. This sensitivity is expressed in the view of balcony railings from the street, the detail of an iron bar on a window, and the smell and sight of fruit trees in nearby gardens.

This school of thought bears a close resemblance to the approach embraced by the anonymous craftsmen who created Japanese folk art between the 13th and 19th centuries (**Figure 5**). Soetsu Yanagi, founder of the Museum of Folk Art in Tokyo, documented this unpretentious yet profound tradition in his book [6] *The Unknown Craftsman*. He described these artifacts as the embodiment of a worldview in which the boundaries between art, philosophy, and the creator's spiritual or "God-given" state of mind are fluid and inseparable.

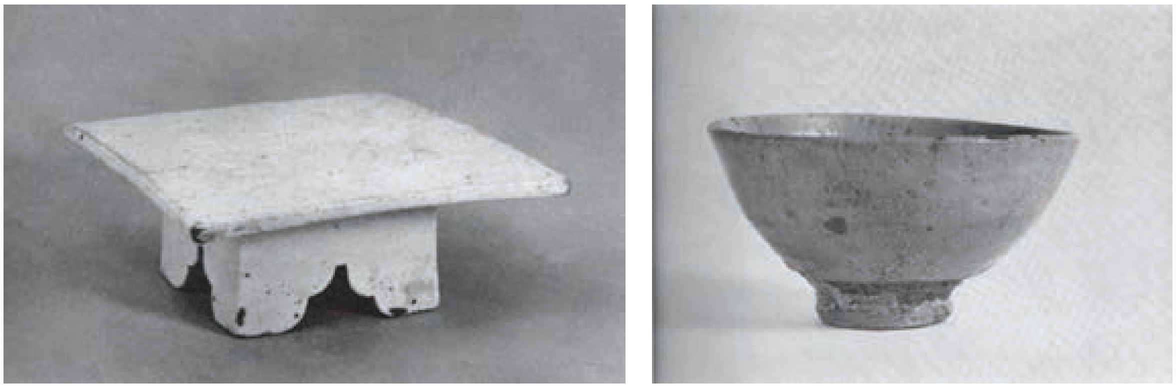


Figure 5. Left to right: Ceremonial stand, porcelain, Yi dynasty (18th century), Korea; Kizaemon Ido tea bowl, Y dynasty (26th century), Korea

This approach was not understood by Le Corbusier, Oscar Nimier, and others around the world, who were part of the mechanistic school of thought, who consciously considered architecture to be no more than icons, environmental sculpture, totally dependent on the arbitrary vision of its creators.

The holistic-organic approach that has been at the forefront of scientific thought for many years, implemented by Alexander in architecture, regards the socio-physical environment as a system, the existence of which depends on the proper, ever-changing interrelations between the parts.

Moreover, the creation and existence of each part depend on the interrelations between that part and the whole. In any organic system, while each element has its own uniqueness and power, it always acts as part of a larger entity to which it belongs and which it complements (**Figure 6**).

Figure 6. Organic system

Within this conceptual framework, urban design, architecture, and interior design are not regarded as separate disciplines, but as components of a continuous and dynamic system. The building and its environment are not perceived as a collection of designed fragments, but as one hierarchical language, in which this historic street, the building, and its interior details are one continuous system [2].

Every design detail, at any level of scale, is derived from the larger whole to which it belongs, which it seeks to enhance and for whose existence it is responsible. The overall feeling of inner wholeness and unity, whether in a building, a street, a neighborhood, or a city, eventually evolves from the proper interrelations between its parts. This led to the focus being about the street at first, rather than the building itself. All the decisions regarding the volume of the building, the construction materials, and the color were generated from the spirit of the street, meaning from the larger whole, it had to be integrated with respect and enhancement.

3. The dialogue between the new building and the existing historical environment

The new building is located on a side pedestrian street adjacent to the food market in the Nahalat Binyamin quarter at the historic center of the city of Tel Aviv. A quarter is a micro-document of the architectural history of Tel Aviv from 1920 to 1930. It was in the 1920s when European architecture was brought to Israel, carried out by Jewish refugee architects who immigrated to Israel from Europe, trying to become integrated with the local oriental architecture, thus named the "Eclectic period" (**Figure 7**).

Figure 7. The historic context: Eclectic architecture of the 1920s and 1930s

The nature of their work until the mid-1930s, as opposed to the Bauhaus, which was imported to Israel as a package deal, was a balance between their affinity to the land of Israel and the use of cross-cultural universal patterns of space brought from their European countries of origin. They consciously attempted to create a new "Israeli" architecture by integrating East and West. A reality (social and physical) that was complex and embodied landscapes, architecture, and local lifestyle.

The patterns of space and the beautiful construction details that were used were not wisely considered as a matter of style, but in a most profound way as the fundamentals of harmony in architecture. These were the timeless cross-cultural patterns that underlie the beauty, comfort, and emotional experience in any building that transcends styles.

Evidently, patterns such as an entrance hall, an arch, or a capital in the column can be found in buildings of all periods and cultures (**Figure 8**).

Figure 8. Left to right: Bayzid Pasa, Masya, Turkey, 14th–15th century; Science Museum Haifa, architect Alexander Browald, 1910; The Residential building, Tel Aviv, by Nili Portugali

These patterns were ignored by the modernists (in general), which resulted in the creation of an architecture devoid of any emotions and meaning.

Preserving the spirit of a historical environment is not a matter of nostalgia and does not necessarily mean a fanatic repetition of its language. The key question I asked myself while standing in the street was, what would be the right language that would create a dialogue between the new contemporary building and the historical street? A language that will preserve and enhance the human spirit of the existing street. None of the conventional approaches was adopted. I was not trying to reconstruct the past, nor was I trying to disassociate myself from it by using an architectural language that would impose an entirely new order.

The façade of this building defines the boundaries of the street and therefore determines the feeling it inspires

(**Figure 3**). The human scale of the building was generated out of the wish to be in harmony with that of the street. A good boundary is an entity that both separates and connects two entities at the same time. The cornices that jut out at the façade, being the extension of the periphery beams and the corner columns protruding from the wall (**Figure 3**), clarifying the structural elements of the building, delineate the common boundary of the building and the space next to it, thus uniting them. The dialogue between the building and the street continues through the high windows as well as the balconies overlooking the street (**Figure 9**). The white-washed facade, gradually changing in color from the ground floor up (**Figure 3**), complements the blue of the sky and the gold of the aluminum frames, painting a harmony that inspires peace and serenity in the street.

Figure 9. The Residential building, Tel Aviv, designed by Nili Portugali

4. The street, the building, and the interior are one continuous organic whole

The walk from the street to the private apartment is via a sequence of transition areas that open onto each other and bring the residents home gradually.

The semi-private garden along the side of the building is entered via a gate from the sidewalk. Orange trees planted along the path adorn the building's main entrance door. The main entrance door leads to a spacious stairwell that opens on each floor onto a spacious lobby leading to the apartments (**Figure 2**). The high windows offering a view of the garden illuminate that space (**Figure 2**).

The gradual transition from the semi-private lobby to the private apartment is via an entrance hall that both connects and separates them, leading gradually to the living areas and out to the balcony (**Figure 8**).

Each apartment was designed slightly differently, according to its specific location in the building, so that it interlocks either with the street or the garden next to it. At the front of the ground floor, there are shops that open onto the pedestrian street, forming an extension to the arts and crafts fair held there.

The back portion of the ground floor features small studio apartments opening onto private gardens. On the higher floors are one- and two-bedroom apartments. Those at the top level have roof terraces that offer a magnificent view of the Mediterranean Sea in the distance (**Figure 10**).

Figure 10. The Residential building, Tel Aviv, designed by the author

5. The association between the contemporary building and tradition

One of the assumptions that immediately arises regarding this building (as well as with other buildings designed by me) is that the building that was built in early 2020 is not a new one but rather a "preservation" or "reconstruction" of a building of the past that had been there much before.

The fact that it feels as if it has been in the street forever makes me feel good, as this is exactly what I was trying to achieve, to design a building that is organically integrated with the street and not alien to it. This assumption is based without any doubt on what we see around us, new buildings that "bark" at their surroundings and are alien to it. Consequently, it is assumed that if a building gives a pleasant feeling of comfort and is integrated in a natural way with its surroundings, it cannot possibly be new. This reality is the result of the iconic architecture, which has knowingly attempted to dissociate itself from the spirit of the place.

So than the next immediate question I am asked is "to what style does it belong? Am I trying to reconstruct an architectural language from the past? My answer to that is, I do not attempt or aim to reconstruct the past or nostalgically trace any style. The association created between the buildings I design and those we know from the past, and the similar emotional experience they generate originates in using the same fundamental timeless patterns of space [4] and the planning process [7] that were used in the past, in any culture and tradition where people aspire to do human architecture with soul. The "art of making" has been brutally ignored by contemporary architecture.

The architectural approach that aims at fulfilling timeless values is by no means a reaction against the contemporary movement, as one might think. On the contrary, it is a genuine attempt to fully use the potential inherited in modern technological society available today, but not as an aim or a value in itself, but as a tool to create a human and friendly environment. Especially at a time when unlimited possibilities are open to us, technology should be used in a controlled, value-oriented, and moral way when approaching the design of the physical environment in which we live. Moreover, the "trademarks" which are currently used as "sustainable development," "green building," "ecological environment," and the like, are no more than a list of dogmatic mantras that refer only to the saving of energy, water, and electricity and the recycling of materials. Without diminishing their importance, there is no reference at all in the list to what should be considered as the central environmental resource, the human being [7]. This results in buildings that look like AI products to say the least, alienated from their concrete physical environment.

The terms “sustainable development” and “green building” thus require a broader definition than the one currently in use.

When the human experience is brought to the front of the agenda, saving energy will inevitably follow. In the past, these were the rules of thumb generated from the daily experience that dictated the design processes.

For example, any human being, whether in his house or at work, needs to have the right temperature for his physical and mental well-being.

The use of thick walls to isolate houses from heat and cold and the use of wind balconies to cool down the house reduced the need and cost of heating and air-conditioning, saving energy. Done without “trademarks” or slogans.

6. Conclusion

In conclusion, it is hoped that a holistic worldview will ultimately prevail in the physical and human environment, generating buildings, streets, neighborhoods, cities, and villages that foster a genuine sense of belonging, places where all will feel truly at home. A worldview that crosses cultures, places, and time.

Disclosure statement

The author declares no conflict of interest.

References

[1] His Holiness the Dalai Lama, 1997, The Joy of Living and Dying in Peace, Harper Collins, India.

[2] Portugali N, 2006, The Act of Creation and the Spirit of a Place / A Holistic-Phenomenological Approach to Architecture, Edition Axel Menges, Stuttgart / London.

[3] Grabow S, Christopher A, 1983, The Search for a New Paradigm in Architecture, Oriel Press, Boston.

[4] Christopher A, Ishikawa S, Silverstein M, 1977, A Pattern Language, Oxford University Press, New York.

[5] Christopher A, 1979, The Timeless Way of Building, Oxford University Press, New York.

[6] Yanagi S, 1972, The Unknown Craftsman; A Japanese Insight into Beauty, Kodansha International, Ltd, Japan.

[7] Christopher A, 2004, The Nature of Order, Center for Environmental Studies, Berkeley.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Theoretical Study and Slip Effect Analysis of Elastic Calculation Methods for Steel-Concrete Composite Beams

Shaohui Chu[1,2,3], Xiangkai Zeng[2]*, Zhixin Guo[4]

[1]Hebei Academy of Building Research Co., Ltd., Shijiazhuang 050000, China
[2]Hebei Construction Engineering Quality Testing Center Co., Ltd., Shijiazhuang 050000, China
[3]Hebei Provincial Key Laboratory of Science and Technology for the Utilization of Solid Waste and Building Materials, Shijiazhuang 050000, China
[4]Hengshui Real Estate Registration Service Center, Hengshui 053000, China

**Author to whom correspondence should be addressed.*

Abstract: Steel-concrete composite beams, due to their superior mechanical properties, are widely utilized in engineering structures. This study systematically investigates the calculation methods for internal forces and load-bearing capacity of composite beams based on elastic theory, with a focus on the transformed section method and its application under varying neutral axis positions. By deriving the geometric characteristics of the transformed section and incorporating a reduction factor accounting for slip effects, a computational model for sectional stress and ultimate load-bearing capacity is established. The results demonstrate that the slip effect significantly influences the flexural load-bearing capacity of composite beams. The proposed reduction factor, which considers the influence of the steel beam's top flange thickness, offers higher accuracy compared to traditional methods. These findings provide a theoretical foundation for the design and analysis of composite beams, with significant practical engineering value.

Keywords: Composite beam; Elastic calculation; Slip effect; Theoretical study

Online publication: October 30, 2025

1. Introduction

Steel-concrete composite beams, leveraging the high strength of steel and the excellent compressive properties of concrete, are extensively applied in bridges, buildings, and other structural systems. In recent years, extensive research has been conducted on calculation methods for composite beams, leading to the development of theoretical models such as the transformed section method, interpolation method, analytical method, and reduced stiffness method. Among these, the transformed section method is widely adopted due to its simplicity and engineering applicability. However, traditional transformed section methods often neglect the slip effect at the steel-concrete interface, resulting in overestimated load-bearing capacity calculations that fail to accurately reflect actual stress conditions.

This study systematically analyzes the application of the transformed section method for calculating internal forces and load-bearing capacity of composite beams based on elastic theory. The analysis addresses two cases: the neutral axis located within the steel beam and within the concrete flange. Corresponding formulas for sectional geometric characteristics and stress distribution are derived. Additionally, a reduction factor accounting for the slip effect, incorporating the influence of the steel beam's top flange thickness, is proposed to enhance the accuracy of load-bearing capacity calculations. This research aims to provide a more reliable theoretical basis for composite beam design, addressing the limitations of traditional methods in handling slip effects.

2. Basic theory

According to the calculation principles of elastic theory, the stress and stiffness of composite beams are calculated using the methods of material mechanics. Therefore, the conversion section is adopted to convert the concrete section into the steel section [1–3].

Suppose there is a steel bar plate at a certain height of the concrete slab. From basic assumption (2), it can be known that $\varepsilon_C = \varepsilon_S$. Then, from basic assumption (1), the stress at a certain height of the concrete slab can be obtained as:

$$\sigma_c=\varepsilon_c E_c \tag{1}$$

Since $\varepsilon_S=\frac{\sigma_s}{E_s},\sigma_s$, where σ_s is the stress of the steel strip, then

$$\sigma_c=\varepsilon_c E_c=\frac{\sigma_s}{E_s}E_c=\frac{1}{\alpha_{ES}}\sigma_s \tag{2}$$

In the formula, σ_C, σ_S represent the compressive stresses of concrete and steel plate, respectively.

ε_C, ε_S respectively represent the strains of concrete and steel strip at the same height on the cross-section;

E_C, E_S respectively represent the elastic modulus of concrete and that of steel;

α_{ES} represents the ratio of the elastic modulus of steel to that of concrete, $\alpha_{ES} = E_S/E_C$.

Based on the fact that the position and magnitude of the resultant force application point remain unchanged, convert the area A_C of the concrete wing plate to the equivalent converted area A_{CS} of the steel.

$$A_{cs}=\frac{1}{\alpha_{ES}}A_c \tag{3}$$

Its physical meaning is: under the conditions of equal strain and constant total internal force, by dividing the area A_C of the concrete by α_{ES}, the area A_C of the concrete slab can be converted into the equivalent cross-sectional area A_{CS} of the steel.

In order to keep the centenary height of the concrete section unchanged before and after conversion, the converted section thickness of the concrete slab remains the same as the original section thickness; that is, only the width of the concrete slab is converted. If the calculated width b_e of the concrete bridge deck of the composite beam.

$$b_e=b_0+b_{c1}+b_{c2}$$

In the formula, b_0 represents the width of the upper flange of the steel beam;

b_{c1}, b_{c2} are the calculated widths of the concrete wing plates measured on the outside and inside of the beam, taken according to the following minimum values: 1/6 of the beam span L, 1/2 of the distance s between the beams, and the actual overextension length of the concrete plate.

Then the converted width of the board is

$$b_{eq}=\frac{1}{\alpha_{ES}}b_e \tag{4}$$

Based on the above principle of conversion section, the section of the steel-concrete composite beam can be converted into an equivalent section of the steel beam, and then the geometric characteristics of the conversion section can be calculated according to the converted section of the steel beam, as shown in **Figure 1**.

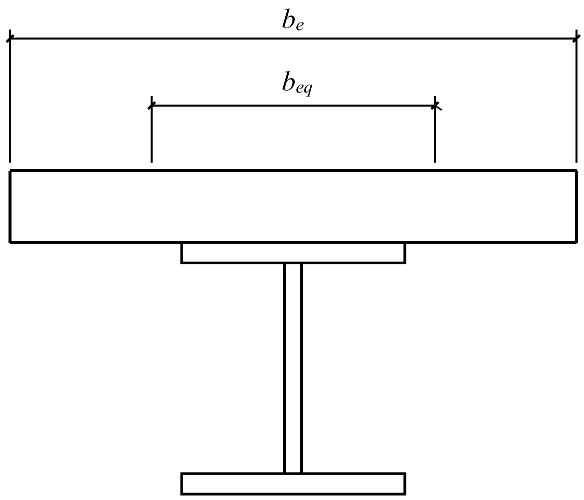


Figure 1. Conversion section of composite beams

3. Calculation method for section resistance distance

After obtaining the geometric characteristics of the converted section, the section stress and ultimate bearing capacity of the composite beam can be directly calculated by using the relevant formulas of material mechanics. Calculate the geometric characteristics of the conversion section respectively for the two cases where the neutralization axis is within the concrete wing plate and outside the concrete plate [4,5].

3.1. The neutralizing shaft is inside the steel beam

The situation where the neutral axis of the composite beam is located within the web of the steel beam is shown in **Figure 2**.

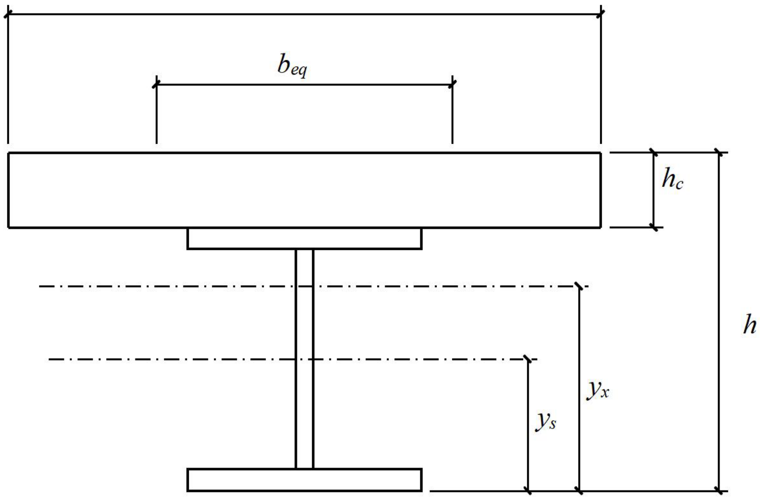


Figure 2. The composite beam and shaft are inside the steel beam

Convert the area of the cross-section A_0

$$A_0 = A_s + A_{cs} \tag{5}$$

Convert the cross-section and the wheelbase distance (with the lower flange edge of the steel beam as the baseline) y_x

$$y_x = \left[A_s y_s + A_{cs}\left(\mathrm{h} - \frac{\mathrm{h}_c}{2}\right)\right] / A_0 \tag{6}$$

Convert the moment of inertia I_0 of the cross-section

$$I_0 = \frac{1}{12} b_{eq} \mathrm{h}_c^3 + A_{cs}\left(\mathrm{h} - y_x - \frac{\mathrm{h}_c}{2}\right)^2 + I_s + A_s (y_x - y_s)^2 \tag{7}$$

The cross-sectional resistance moment at the edge of the lower flange of the steel beam

$$W_{0s}^{b} = \frac{I_0}{y_x} \tag{8}$$

The cross-sectional resistance distance of the upper edge of the concrete

$$W_{0c}^{t} = \frac{I_0}{\mathrm{h} - y_x} \tag{9}$$

3.2. The neutralizing axis is located within the concrete wing plate

The situation where the central axis of the composite beam is located within the concrete wing plate is shown in **Figure 3**.

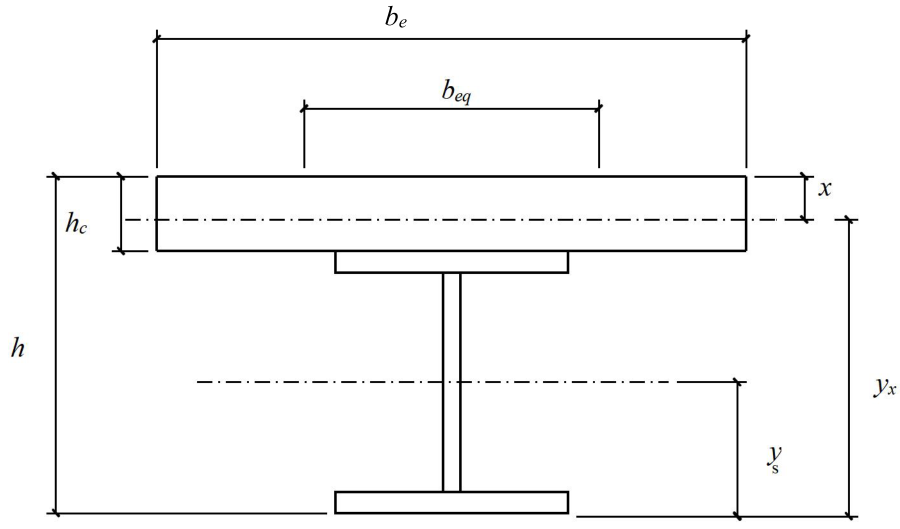


Figure 3. Composite beam and shaft inside the concrete wing

Firstly, based on the area-moment equilibrium equation around the neutral axis, the distance x between the neutral axis and the upper edge of the composite beam can be solved

$$\frac{1}{2}b_{eq}x^2\text{-}A_s(\text{h-}y_s\text{-}x)=0 \tag{10}$$

If the concrete in the tensile zone is ignored, then convert the area of the cross-section

$$A_0=b_{eq}x+A_{cs} \tag{11}$$

Convert the cross-section and the wheelbase distance (taking the lower flange edge of the steel beam as the baseline)

$$y_x=\text{h-}x \tag{12}$$

Convert the moment of inertia I_0 of the cross-section

$$I_0=\frac{1}{3}b_{eq}x^3+I_s+A_s(\text{h-}y_s\text{-}x)^2 \tag{13}$$

The cross-sectional resistance moment at the edge of the lower flange of the steel beam

$$W_{0s}^b=\frac{I_0}{y_x} \tag{14}$$

The cross-sectional resistance distance of the upper edge of the concrete

$$W_{0c}^t=\frac{I_0}{x} \tag{15}$$

4. Analysis of the impact of the slip effect

4.1. The ultimate bearing capacity of the composite beam and the normal internal force of the section during sliding are not considered

The section resistance moment of the converted section was obtained earlier. Then, the elastic ultimate bearing capacity is calculated as

$$M_y = W_{0s}^b f_y \tag{16}$$

The normal stress of the cross-section at the edge of the lower flange of the steel beam

$$\sigma_{0s}^b = \frac{M}{W_{0s}^b} \tag{17}$$

The normal stress of the cross-section at the upper edge of the concrete wing slab

$$\sigma_{0c}^t = \frac{M}{\alpha_{ES} W_{0c}^t} \tag{18}$$

4.2. Consider the ultimate bearing capacity of the composite beam and the normal internal force of the section during sliding

In the elastic calculation, the slip between the steel beam and the concrete flange was ignored. However, in actual engineering, due to the existence of slip, the actual elastic flexural bearing capacity of the section is less than that obtained by the converted section method. Under the same bending moment, the normal stress of the section considering slip will also be greater than the calculation result obtained by the converted section method [6,7].

If other assumptions remain unchanged, considering slip, Hypothesis (2) is changed to indicate that there is relative slip between the steel beam and the concrete wing plate. However, it is still assumed that their curvatures are the same, and the additional stress caused by slip strain is linearly distributed, as shown in **Figure 4**.

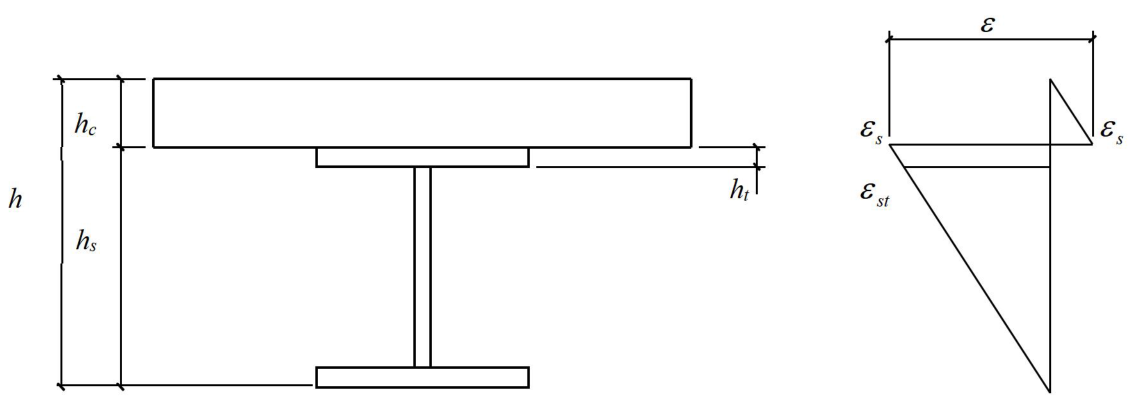


Figure 4. Additional strain caused by slip strain

The dimensions and strains of each part of the composite beam are shown in **Figures 2–4**. From the assumption, the relationship between the additional curvature and strain is as follows

$$\Delta\varphi = \frac{\varepsilon}{\mathrm{h}} = \frac{\varepsilon_S}{\mathrm{h}_s} = \frac{\varepsilon_C}{\mathrm{h}_c} = \frac{M\xi}{EI} \tag{19}$$

In the formula, ε is the relative slip strain; ε_S and ε_C are the slip strains at the junction of the steel beam and the concrete flange, respectively. ξ is the stiffness reduction coefficient; EI is the stiffness of the converted section.

The strain at the junction of the web and the upper flange of the steel beam is

$$\varepsilon_{st} = \frac{h_s - h_t}{h_s}\varepsilon_s \tag{20}$$

The additional resultant force of the web of the steel beam is

$$\Delta N_1 = \frac{1}{2}E_s \varepsilon_{st} A_w \tag{21}$$

In the formula, A_w represents the web area of the steel beam

The additional resultant force of the flange plate on the steel beam is

$$\Delta N_2=\frac{1}{2}E_s(\varepsilon_{st}+\varepsilon_s)A_t \tag{22}$$

In the formula, A_t represents the area of the upper flange of the steel beam

Then the additional bending moment of the cross-section is

$$\Delta M\ =\Delta N_1 d_1+\Delta N_2 d_2 \tag{23}$$

In the formula, d_1 and d_2 are respectively the distances from the points of application of the additional resultant force of the web and upper flange of the steel beam to the points of application of the additional resultant force of the concrete.

$$d_1=\frac{1}{3}（\mathrm{h}_s-\mathrm{h}_t）+\mathrm{h}_t+\frac{1}{3}\mathrm{h}_c=\frac{1}{3}(\mathrm{h}+2\mathrm{h}_t) \tag{24}$$

$$d_2=\frac{1}{2}\mathrm{h}_t+\frac{1}{3}\mathrm{h}_c \tag{25}$$

Substitute to obtain the additional bending moment

$$\Delta M=\frac{E_s M\xi}{6EI}\left[(\mathrm{h}_s-\mathrm{h}_t)(\mathrm{h}+2\mathrm{h}_t)A_w+\left(\mathrm{h}_s-\frac{\mathrm{h}_t}{2}\right)(3\mathrm{h}_t+2\mathrm{h}_c)A_t\right] \tag{26}$$

Then the actual bending moment of the composite beam is

$$M_p=M-\Delta M \tag{27}$$

Let $M_p=\beta M$, then the slip reduction coefficient β has the following expression

$$\beta=1-\frac{\mathrm{h}_s E_s\xi}{6EI}\left[\left(1-\frac{\mathrm{h}_t}{\mathrm{h}_s}\right)(\mathrm{h}+2\mathrm{h}_t)A_W+\left(\mathrm{h}_s-\frac{\mathrm{h}_t}{2}\right)(3\mathrm{h}_t+2\mathrm{h}_c)A_t\right] \tag{28}$$

Calculation of normal stress in cross-section

$$\sigma=\frac{M-\Delta M}{W}=\frac{\beta M}{W} \tag{29}$$

In the formula, W represents the corresponding cross-sectional resistance distance obtained by the conversion section method.

The flexural bearing capacity in the elastic limit state is

$$M_{py}=\beta M_y \tag{30}$$

When conducting elastic theory analysis, the influence of slip was taken into account. Through the calculation of the additional bending moment, the reduction coefficient of the elastic ultimate flexural bearing capacity considering slip was obtained. The reduction coefficient derived in this paper takes into account the influence of the thickness of the upper flange of the steel beam, and the result is more accurate.

5. Conclusion

This paper provides an in-depth study of the elastic calculation method for steel-concrete composite beams, systematically explaining the theoretical foundation of the equivalent section method and its application at different neutral axis positions. In addressing the impact of interface slip on bearing capacity, a reduction factor considering the thickness of the upper flange of the steel beam is derived, significantly improving the calculation accuracy. The research results indicate that the slip effect cannot be overlooked, and its influence on the bending capacity and section stresses of the composite beam must be fully considered in the design. The theoretical derivations and calculation models presented in this paper provide an important reference for the engineering design and analysis of composite beams. Future work could involve further validation of the model's applicability through experimental data and the exploration of computational methods for the nonlinear stage, expanding its application under complex conditions.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Fang LX, Song QG, 2000, Calculation of Elastic Stiffness and Ultimate Strength of Partially Connected Composite Beams. Industrial Construction, (01): 47–50.

[2] Nie JG, Li SJ, Li CG, et al., 2003, Experimental Study on Internal Force Redistribution in Prestressed Steel-Concrete Continuous Composite Beams. Industrial Construction, (12): 12–14 + 5.

[3] Jiang XG, Ju JS, Fu XR, 2007, Elastic Stress Calculation of Steel-Concrete Composite Beams Considering Slip Effects. Engineering Mechanics, (01): 143–146 + 142.

[4] Xie HY, Zheng WZ, 2010, Experimental Study on the Mechanical Performance of Encased Steel Box-Concrete Continuous Composite Beams. Journal of Harbin Institute of Technology, 42(02): 186–192.

[5] Zhou DH, Sun LL, Fan J, et al., 2011, Stress Calculation Method for Composite Beams with Elastic Shear Connections. Engineering Mechanics, 28(03): 157–162.

[6] Huang Q, Guo ZY, Wan SC, et al., 2017, Study on the Calculation Method for Elastic Flexural Load-Bearing Capacity of Steel-Concrete Composite Beam Bridges. China Journal of Highway and Transport, 30(03): 167–174.

[7] Ye HW, Jiang CC, Huang A, et al., 2024, Elastic Bending Deformation Calculation Method for Steel-Concrete Composite Beams Based on Trigonometric Series Solutions. Journal of Building Structures, 45(05): 253–261.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Construction of a Green Evaluation System for Prefabricated Buildings Based on BIM Technology from the Perspective of Carbon Footprint

Lingfang Li*

Guangdong University of Business and Technology, Zhaoqing 526000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: Driven by the goal of carbon neutrality, prefabricated buildings, as an important form of green construction, have become a key focus in the study of lifecycle carbon footprint management. Based on this, this paper starts from the perspective of carbon footprint and combines the digital and visual advantages of BIM technology to construct a green evaluation system for prefabricated buildings. It explores the carbon emissions in each stage of the building and proposes corresponding improvement measures, aiming to provide necessary references for the low-carbon transformation of prefabricated buildings.

Keywords: Carbon footprint perspective; BIM technology; Prefabricated buildings

Online publication: October 30, 2025

1. Introduction

Under the background of global climate change, the construction industry, as a major source of carbon emissions, is in urgent need of decarbonization transformation. Prefabricated buildings, characterized by their standardized design and factory production, are regarded as a key to reducing on-site pollution. BIM technology, by constructing a three-dimensional digital model, can achieve seamless integration of design, construction, and operation and maintenance data and provide technical support for accurately tracking carbon emissions. Thus, it can effectively promote the transition of prefabricated buildings towards the goal of "zero-carbon construction" and provide a scientific basis for the low-carbon development of the industry.

2. Framework construction of the green evaluation system for prefabricated buildings based on BIM technology

2.1. Design of the indicator system

2.1.1. Primary indicators

Based on the framework of the whole-lifecycle theory, the green evaluation system for prefabricated buildings driven by BIM technology has established the following four primary-level evaluation dimensions: resource consumption, environmental impact, economic benefits, and technological innovation [1]. The resource consumption dimension systematically characterizes the utilization efficiency of materials, energy, and water resources throughout the entire lifecycle of a building, highlighting the orientation of resource conservation. The environmental impact dimension strengthens the goal of low-carbon environmental protection by quantifying carbon emission intensity, pollutant emission control levels, and ecological impact effects. The economic benefits dimension achieves dynamic synergy between economic sustainability and environmental benefits by comprehensively calculating the cost-benefit of the entire lifecycle and the economic value of carbon emission reduction. The technological innovation dimension drives a technology-led green transformation by measuring the breadth of BIM technology application, the maturity of intelligent management, and the ability to innovate in processes. These four dimensions are intercoupled and organically coordinated. Together, they construct a systematic evaluation framework that covers the entire chain of "design–production–construction–operation and maintenance," ensuring the scientific and systematic nature and practical operability of the evaluation results.

2.1.2. Secondary indicators

Under the systematic support of the primary evaluation framework, the secondary indicators are scientifically broken down into quantifiable operational dimensions. The resource consumption dimension is further divided into material utilization rate, the proportion of renewable energy, and the rate of water resource recycling. The environmental impact dimension covers carbon emission intensity per unit area, construction waste recycling rate, and indoor environmental quality indicators [2]. The economic benefit dimension includes the full-lifecycle cost, carbon trading revenue, and operation and maintenance energy-saving benefits. The technological innovation dimension involves BIM model accuracy, the coverage rate of intelligent management systems, and the innovation index of prefabricated construction technology. The above-mentioned secondary indicators, by accurately measuring the efficiency of resource utilization, the intensity of environmental load, the economic return benefits, and the level of technological advancement, provide a rigorous basis for the construction of tertiary indicators, thus systematically ensuring the clear-cut hierarchy and application-oriented nature of the evaluation system.

2.1.3. Tertiary indicators

As the refined implementation units of the evaluation system, tertiary indicators focus on standardized parameters that can be quantitatively monitored, ensuring the precision and operability of the evaluation process. In the dimension of resource consumption, key indicators include the reuse rate of prefabricated components, the proportion of solar water heating systems, and the utilization of non-traditional water sources [3]. The environmental impact dimension comprises the carbon emission simulation value during the design phase ($kgCO_2/m^2$), the dust emission concentration during the construction phase (mg/m^3), and the energy consumption intensity during the operation and maintenance phase ($kWh/m^2 \cdot year$). The economic benefit dimension involves the payback period of initial investment, the economic benefit of carbon emission reduction ($yuan/tCO_2$), and the proportion of reduced equipment failure rate. The technological innovation dimension covers the synchronization rate of BIM models with IoT data, the coverage rate of automated production lines, and the number of new connection node developments. The above-mentioned indicators precisely characterize the green performance of the entire lifecycle of a building through structured numerical values, providing a scientific and quantifiable evaluation benchmark for the low-carbon practice of BIM-empowered prefabricated buildings. This effectively supports the refined management and continuous optimization of green buildings.

2.2. Evaluation model and method

The green evaluation system for prefabricated buildings based on BIM technology constructs a systematic evaluation model by integrating dynamic carbon footprint accounting, multi-source weight allocation, and a comprehensive evaluation mechanism. The carbon footprint accounting module relies on the BIM platform and uses the lifecycle assessment method to extract structured data such as material quantities, component geometric parameters, and process parameters from the entire lifecycle dimension, ranging from raw material extraction, production and transportation, construction and installation to operation, maintenance, and demolition. It also couples with the regional carbon emission factor database to dynamically quantify the energy consumption intensity and total carbon emissions of each stage, forming a dynamic carbon emission inventory covering the entire lifecycle of the building [4,5]. In the weight determination phase, a strategy combining the analytic hierarchy process and the judgment of industry experts is adopted. By constructing a multi-dimensional judgment matrix that includes resource consumption, environmental impact, economic benefits, and technological innovation, the weight coefficients of indicators at each level are calculated to ensure that the weight allocation is both theoretically rigorous and practically applicable. In the comprehensive evaluation stage, the fuzzy comprehensive evaluation method or the TOPSIS method is preferred. The former deals with the fuzziness in the evaluation process through membership functions and is suitable for complex systems with multiple indicators and levels. The latter, based on the principle of sorting by the ideal solution, scientifically ranks the schemes by calculating their proximity to the best and worst solutions. Both methods can effectively integrate the BIM data characteristics and the weight system to output a comprehensive score of the green performance of prefabricated buildings and optimization paths, providing a precise and operable theoretical basis and practical support for low-carbon construction decision-making.

3. Key empowerment evaluation paths of BIM technology for prefabricated buildings from the perspective of carbon footprint

3.1. Design phase

Starting from the perspective of carbon footprint management, BIM technology, with its digital integration characteristics, provides a systematic optimization path for the design phase of prefabricated buildings, focusing on two major dimensions: component-level detailed design and dynamic carbon emission simulation. In terms of component optimization, the BIM model, relying on its three-dimensional parametric design mechanism, achieves the standardization and precise configuration of prefabricated building components. Specifically, by constructing a standardized component database and setting key parameters such as geometric dimensions, connection node topology, and material properties, the system can generate multiple-scheme decomposition models. Considering transportation loading constraints and lifting process requirements comprehensively, the system evaluates different decomposition strategies from multiple dimensions, covering key indicators such as component production efficiency, on-site assembly complexity, and material loss rate [6]. For example, simulation analysis based on the loading rate of transportation vehicles can optimize the volume of components to reduce the frequency of transportation, effectively reducing carbon emissions in the transportation phase. Meanwhile, the standardized component design significantly improves the reuse rate of factory molds, reducing energy consumption and construction waste generation in the production phase, thus achieving a substantial reduction in the lifecycle carbon footprint.

In the carbon emission simulation aspect, BIM technology deeply integrates a dynamic quantification module, which supports multi-dimensional comparison of carbon emissions for different design schemes. This module extracts data on component material quantities, construction process parameters, and energy consumption from the BIM model and couples with a regional carbon emission factor database to calculate the total carbon emissions across all stages, including design, production, transportation, and construction in real time. By parametrically adjusting core variables such as structural systems, material types, and connection methods, it generates comparative analysis curves of carbon emissions, providing data support for design decision-making [7]. Typical application cases include comparative analysis of the lifecycle carbon emissions of steel and concrete structures, as well as quantitative assessment of the impact of different insulation materials on energy consumption during the operation and maintenance phase of buildings. This drives the design mode to transition from experience-based to data-driven low-carbon transformation. This process not only enhances the precision of carbon emission reduction in the design phase but also constructs the theoretical framework and practical path for carbon management across the entire chain of prefabricated buildings.

3.2. Production phase

Based on the theoretical framework of carbon footprint assessment, BIM technology drives the low-carbon transformation of the production phase of prefabricated buildings through the construction of a data interaction system and a dynamic monitoring mechanism. In terms of data integration, the BIM model is dynamically coupled with the factory production system throughout the entire process, such as size specifications, material properties, and connection node topology. The geometric parameters of components are transmitted in real time to the numerical control production line through a standardized interface, accurately guiding automated cutting, welding, and assembly processes, effectively suppressing material waste caused by human-induced deviations. Meanwhile, the Internet of Things sensor network deployed at the production site continuously collects dynamic data such as equipment operating conditions, raw material consumption rates, and finished product pass rates, which in turn calibrates the production parameters in the BIM model, forming a closed-loop optimization mechanism of "design-manufacturing" [8]. For example, when the actual steel reinforcement quantity deviates from the model-predicted threshold, the system automatically triggers the adaptive adjustment of the reinforcement scheme to avoid material redundancy. If the mold wear rate exceeds the preset standard, the BIM model dynamically optimizes the maintenance cycle to reduce energy losses caused by unplanned shutdowns. In the carbon emission accounting aspect, the BIM platform integrates modules for real-time energy monitoring and dynamic correction of carbon factors to ensure high-precision quantification of carbon emission data. The intelligent metering terminals configured on the production line, including electricity meters and gas meters, continuously record energy consumption data at the process level. Coupled with the regional power grid carbon emission factor database, this enables real-time dynamic calculation of carbon emissions per component. When the energy structure of the factory changes, the system immediately updates the carbon emission factors and calibrates the accounting model to eliminate evaluation deviations caused by static factors. This dynamic control system not only makes the carbon footprint of the production phase visible and traceable but also provides precise data support and a theoretical basis for corporate process optimization decisions and energy structure transformation.

3.3. Transportation and construction phase

Starting from the theoretical framework of carbon footprint management, BIM technology drives the low-carbon control of the transportation and construction phases of prefabricated buildings through the collaborative mechanism of intelligent transportation route optimization and 4D construction process simulation. In terms of transportation optimization, the BIM platform integrates geographic information systems and real-time traffic flow data to build a dynamic route-planning model. Based on the size, weight, loading sequence, and transportation constraints of components, the model generates multiple route plans and quantifies the fuel consumption intensity and total carbon emissions of each plan. By comparing the congestion index of highways and urban roads and the carbon emission coefficient per unit distance, the model recommends route optimization plans that avoid peak traffic periods, effectively reducing additional energy consumption during idling [9,10]. Meanwhile, by optimizing loading strategies based on the size characteristics of components, the model improves vehicle space utilization, reduces transportation frequency and total mileage, and directly cuts the carbon footprint of the transportation phase. In the construction simulation aspect, the 4D construction simulation technology of BIM integrates the time dimension and resource scheduling data to realize the virtual rehearsal of the entire construction process. The system generates dynamic simulations of key processes such as component hoisting and node connection based on the BIM model, identifying structural collision conflicts and process interference risks in advance to avoid material waste and machinery idling caused by on-site rework. Specifically, by simulating the match between the working range of tower cranes and the storage position of components, the system optimizes the layout of the construction site to reduce secondary handling. By parametrically adjusting the working sequence of multiple trades, it eliminates process interference and reduces energy consumption. This "rehearsal-optimization" mechanism promotes a shift in construction carbon emission management from passive statistics to active control, significantly enhancing the carbon emission reduction efficiency and management precision of prefabricated buildings throughout their entire lifecycle.

3.4. Operation and maintenance phase

The deep collaborative integration of BIM and the Internet of Things (IoT) constructs a systematic support path for the full-lifecycle carbon management of prefabricated buildings during the operation and maintenance phase. Relying on a smart sensor network, the BIM + IoT integrated platform collects real-time data on the operation of building equipment, environmental conditions, and energy consumption, dynamically mapping this data to the BIM model to form a multi-dimensional real-time data layer. Through the spatial topological association mechanism of the BIM model, the system precisely binds energy consumption data to specific spatial units and equipment attributes, enabling targeted identification of high energy consumption areas. Coupled with a regional power grid carbon emission factor database, it quantifies the carbon emission intensity and distribution characteristics of each link in real time. When sensors detect abnormal fluctuations in the energy consumption of lighting circuits, the BIM model can immediately associate the type of lighting fixtures, their operating duration, and the corresponding carbon emissions, providing a basis for optimizing maintenance decisions, such as adjusting the timing of lighting on and off or implementing energy-saving equipment replacements [11,12]. At the same time, the facility management database, using the BIM model as a data carrier, integrates the full-lifecycle information of equipment, typically including purchase time, maintenance logs, and replacement cycles. Coupled with energy consumption monitoring data, it constructs a dynamic carbon footprint tracking system. This system supports the generation of carbon emission analysis reports based on multiple dimensions, such as time series, spatial distribution, and equipment categories, intuitively presenting the evolution patterns and key driving factors of carbon emissions during the operation and maintenance phase. For example, by comparing the carbon emission data of air-conditioning systems over different years, it is possible to quantitatively assess the effectiveness of energy efficiency improvements or the impact mechanisms of equipment aging on the carbon footprint. This provides empirical support for formulating refined low-carbon maintenance strategies, such as optimizing equipment start and stop parameters and promoting the application of distributed renewable energy sources, thereby achieving dynamic regulation and continuous optimization of carbon emissions during the operation and maintenance phase of prefabricated buildings.

4. Conclusion

In constructing the green evaluation system for prefabricated buildings based on BIM technology, by quantifying carbon emissions throughout the entire lifecycle and integrating multi-source data and dynamic models, the green evaluation can be transformed from being "result-oriented" to "process-controlled." This significantly enhances the accuracy of carbon emission accounting, thereby helping to achieve the ultimate goal of emission reduction for prefabricated buildings.

Disclosure statement

The author declares no conflict of interest.

References

[1] Shi Z, Zou E, Pi J, et al., 2025, Analysis of Carbon Footprint Model of Buildings Based on BIM. Building Mechanization, 46(04): 47–50.

[2] Li J, 2024, Analysis of Carbon Emissions and Carbon-Reduction Strategies in the Entire Life Cycle of Prefabricated Buildings. Building Safety, 39(11): 30–35.

[3] Yang W, Song P, Chen Z, et al., 2024, Research on Carbon Footprint of Prefabricated Concrete Buildings in the Materialization Stage Based on BIM Technology. Zhejiang Architecture, 41(02): 65–69.

[4] Song P, Lv Y, Qian Y, et al., 2023, Design and Application of BIM-Based Carbon Emission Calculation System for Prefabricated Buildings. Science & Technology Bulletin, 39(11): 28–32 + 39.

[5] Cheng X, Fu J, Xu J, et al., 2023, Influence of Component Parameters of Prefabricated Concrete Frame Structures on Carbon Emissions. Journal of Zhejiang Sci-Tech University (Natural Science), 49(03): 404–414.

[6] Gu Y, Hao J, Zhang J, et al., 2024, Analysis and Discussion on the Revision of Evaluation Indicators for Green Building Materials of Ready-Mixed Mortar. Concrete World, (12): 67–73.

[7] Tang Y, Mao X, Li J, 2024, Research on Carbon Footprint Accounting of Pallet Unit Box Life Cycle. Packaging Engineering, 45(21): 233–239.

[8] Zhou Q, Liu M, Zhang L, et al., 2024, Research and Practice on Carbon Footprint Accounting of Leather Products under the "Dual Carbon" Goal. Leather Science and Engineering, 34(06): 40–46.

[9] Tan X, Li H, Wang Z, et al., 2024, Analysis of Changes in the Carbon Footprint of Wheat Life Cycle in Different Provinces from 2015 to 2020. Chinese Journal of Agrometeorology, 45(08): 809–821.

[10] Zheng P, 2024, Carbon Footprint Measurement and Evaluation Methods of Photoelectric Display Products. Metrology & Measurement Technology, 51(07): 104–106.

[11] Yu M, Wang F, 2024, Comparative Assessment of the Life-Cycle Carbon Footprint of Hydrogen-Based Green

Industrial Products and Traditional Processes. Jiangsu Science & Technology Information, 41(07): 122–127.
[12] Tong S, Zhao K, Liang H, et al., 2024, Research on Carbon Footprint of Magnesium Alloy Rear-Hinged Door Based on Life-Cycle Assessment. Foundry Engineering, 48(02): 53–56.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Technical Management and Risk Management Practices for a High-Rise Public Building Project in Guangzhou Nansha Free Trade Zone

Fuxuan Lin*

Shenzhen 518000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: The construction project of a non-super high-rise public building in Guangzhou's Nansha Free Trade Zone faces unique challenges. The project established a full-cycle technical management system, encompassing technical management across various sectors and BIM collaboration. Simultaneously, it introduced advanced technical management such as deep foundation pits and core tube construction, along with a risk management system and special weather response strategies. Through these measures, the project achieved numerous significant results, forming a unique management paradigm that offers valuable insights for similar engineering projects.

Keywords: Nansha Free Trade Zone; Non-super high-rise public building; Engineering management

Online publication: October 30, 2025

1. Introduction

With the development of the construction industry, non-super high-rise public building projects face numerous challenges and opportunities. The *China (Guangdong) Pilot Free Trade Zone Overall Plan*, issued in 2015, provided policy support for the construction of the Nansha Free Trade Zone in Guangzhou, reflecting the strategic deepening of China's free trade pilot zone policy over the past decade [1]. Against this backdrop, a non-super high-rise public building project in the Nansha Free Trade Zone, due to its unique geographical location and project characteristics, holds significant research value in engineering technology management, risk management, and other areas. This project involves complex structural design, integration of mechanical and electrical systems, and responses to special weather conditions. The adoption of a full-lifecycle management system for materials and equipment has effectively enhanced management efficiency and engineering quality [2], while also achieving remarkable results in cost control and social benefits. Its management model and experiences have certain reference value for non-super high-rise public building projects and provide guidance for improving engineering management under the policy environment of the free trade zone.

2. Project overview and technical management framework

2.1. Overview of Nansha Free Trade Zone engineering projects

The public building project in Guangzhou Nansha Free Trade Zone boasts a unique profile. Located within the Free Trade Zone and facing coastal geological conditions, this project poses special requirements for engineering construction. The building comprises multiple clusters and adheres to specific technical parameters. Notably, the structural characteristics of the public building are prominent, and the design and construction of its structural system are challenging, requiring consideration of various factors such as wind loads and seismic effects. Additionally, the electromechanical system is extremely complex, encompassing multiple subsystems such as water supply and drainage, electrical, and heating and ventilation, which necessitate high coordination and integration to ensure the normal operation of the building. To effectively navigate these complexities and achieve the dual objectives of cost excellence and quality, the project management draws upon and implements advanced high-quality management processes [3].

2.2. Construction of a full-cycle technology management system

A non-super high-rise public building in the Nansha Free Trade Zone of Guangzhou City boasts a unique engineering profile. Located within the free trade zone and facing coastal geological conditions, it imposes special requirements on engineering construction. The building comprises multiple clusters, possesses specific technical parameters, and exhibits notable structural characteristics, necessitating consideration of various factors such as wind load and seismic effects [4,5]. The structural system design and construction of this project are challenging. Additionally, the electromechanical system is extremely complex, encompassing numerous subsystems such as water supply and drainage, electrical, heating and ventilation, etc. High coordination and integration among these subsystems are required to ensure the normal operation of the building. These characteristics pose numerous challenges to the engineering technology management of this project.

3. Key construction technology management practices

3.1. Technical management of deep foundation pit and pile foundation engineering

In non-super high-rise public building projects in the Nansha Free Trade Zone of Guangzhou, technical management of deep foundation pits and pile foundation engineering is crucial. For the construction of waterproof curtain using triaxial mixing piles, precise control of construction parameters is required to ensure uniform mixing, continuous pile body, and achieve good waterproofing effect. For the control of the verticality of prestressed pipe piles, strict control is needed from multiple aspects such as the installation and commissioning of pile drivers, lifting and positioning of pile bodies, and real-time monitoring during the construction process to ensure that the pipe piles are driven vertically into the ground and meet design requirements. In addition, a linkage mechanism for foundation pit monitoring data is established, integrating various monitoring data such as displacement, settlement, and water level, to analyze data trends in a timely manner, respond quickly when abnormalities occur, and ensure the safety and stability of deep foundation pit and pile foundation engineering construction.

3.2. Structural construction quality control

In non-super high-rise public building projects in the Nansha Free Trade Zone of Guangzhou, the application of the core tube construction system ensures construction safety and efficiency. This system features high automation and rapid construction progress, effectively shortening the construction period and improving construction quality. The high-strength concrete pumping process is a key link in structural construction. By reasonably selecting pumping equipment and optimizing concrete mix proportions, it ensures that high-strength concrete can be smoothly transported to the designated location, meeting structural strength requirements. The integrated management of the structural health monitoring system is crucial for construction quality control. This system can monitor structural deformation, stress, and other parameters in real time, promptly identify potential problems, and take corresponding measures to ensure the safety and stability of the structure during construction.

4. Implementation of engineering risk management system

4.1. Risk identification and assessment mechanism

4.1.1. Construction of a comprehensive process risk checklist

The implementation of an engineering risk management system requires the construction of a comprehensive risk checklist. Firstly, it is necessary to conduct a comprehensive identification of potential risks, taking into account various stages of the project and various influencing factors. For example, a non-super high-rise public building project in Nansha Free Trade Zone, Guangzhou, established a 12-category risk matrix including geological risks, high-altitude operation risks, cross-construction risks, etc., covering up to 62 risks. Through the analysis of similar projects and the summary of past experience, the possible links and manifestations of various risks were sorted out. After identifying risks, they need to be evaluated to determine the level of risk, so as to take targeted management measures subsequently. This process requires a combination of qualitative and quantitative methods, such as the Analytic Hierarchy Process (AHP), considering the likelihood of risk occurrence and the severity of consequences, providing accurate and effective basis for engineering risk management [6].

4.1.2. BIM risk simulation and prediction

In the implementation of the engineering risk management system, BIM risk simulation and prediction are crucial components. Tools such as Revit and Dynamo are utilized for digital rehearsals, including curtain wall installation collision simulation and electromechanical integrated pipeline conflict detection. By accurately modeling and simulating the curtain wall installation process, potential collision risk points, such as spatial conflicts between different components, can be identified in advance. Similarly, for electromechanical integrated pipelines, conflicts such as intersections and overlaps that may arise during actual installation can also be detected. This BIM-based risk simulation and prediction enables the discovery of potential risks before project implementation, provides accurate data support for risk assessment, and aids in the formulation of effective risk response measures [7]. Consequently, it helps reduce risk losses during project implementation and enhance project quality and efficiency.

4.2. Risk response measure system

4.2.1. Strategies for dealing with special weather conditions

In a non-super high-rise public building project located in the Nansha Free Trade Zone of Guangzhou, effective response strategies have been formulated for special weather conditions, especially during the typhoon season, through a systematic decision-making process. For the curtain wall unit panels, a temporary fixing scheme has been devised to ensure the stability of the panels during typhoon weather, preventing displacement or even detachment caused by strong winds, thereby safeguarding the building’s appearance and the safety of surrounding personnel. Additionally, a wind prevention plan has been established for tower cranes, which operate at heights and are significantly affected by wind forces. The plan specifies detailed operational guidelines for tower cranes under different wind levels, such as reinforcement measures before a typhoon arrives and the parking position of the lifting arm, to prevent serious accidents such as collapse caused by strong winds [8]. This ensures that construction safety and progress are not unduly affected by special weather conditions..

4.2.2. Cross-construction coordination mechanism

In terms of the coordination mechanism for cross-construction, it is crucial to establish standards for the handover of various professional procedures. Clarifying the handover requirements and quality standards for each discipline at different construction stages ensures the continuity and accuracy of construction, avoiding risks caused by improper procedure connections. Meanwhile, the development of a mobile collaborative management system provides strong support for construction interface management. Through this system, construction teams can share information such as construction progress, problems, and solutions in real time, strengthening communication and collaboration. Management personnel can grasp the on-site situation in a timely manner, effectively coordinate and schedule cross-construction, promptly resolve potential conflicts and contradictions, improve construction efficiency, and reduce risks caused by poor information flow or ineffective coordination.

5. Analysis of the effectiveness of management practices

5.1. Verification of technical management achievements

5.1.1. Analysis of quality acceptance pass rate

The project has achieved remarkable results in terms of the quality acceptance pass rate. The detection rate of Class I piles in the pile foundation testing reached 96%, indicating that the quality of the pile foundation works is high and meets the relevant standard requirements. The verticality deviation of the main structure is $\leq$H/2000, reflecting the precision and high quality of the main structure construction. These measured data verify the quality level of the project under technical management from different aspects. The high quality of the pile foundation and the precise construction of the main structure have laid a solid foundation for the overall project quality, reflecting that strict control over each key link in the practice of technical management has achieved good results and effectively ensured the pass rate of the project quality acceptance.

5.1.2. Benefits of new technology application

Prefabricated construction technology has demonstrated significant advantages in a non-super high-rise public building project in Nansha Free Trade Zone, Guangzhou. Through efficient assembly of prefabricated components, the construction period has been greatly shortened, saving 47 days. This not only accelerates the project progress but also potentially brings a series of chain benefits, such as economic benefits generated by early commissioning. At the same time, the application of the smart construction site system has also achieved good results. This system optimizes management processes through information technology, achieves real-time monitoring and precise management of the construction site, and effectively reduces management costs by 18%. This cost reduction enhances the economic benefits of the project and provides strong support for quality and safety management, ensuring the smooth progress of the project.

5.2. Risk management performance evaluation

5.2.1. Risk accident statistics

The project's risk management system demonstrated considerable effectiveness, as evidenced by accident statistics throughout the construction phase. Records indicate zero major safety incidents and a notable reduction in minor accidents, with the total accident frequency rate 22% lower than the industry average for comparable projects. This outcome is largely attributed to the predictive capabilities of the BIM-based risk simulation platform, which enabled proactive identification and resolution of over 85% of potential spatial and procedural conflicts prior to on-site execution [9]. Furthermore, the systematic application of a social sustainability assessment framework throughout the project lifecycle facilitated enhanced stakeholder coordination and oversight of subcontractors, effectively mitigating risks associated with workforce management and operational interfaces [10]. The integration of these structured preemptive measures substantiates the robustness of the implemented risk management protocols.

5.2.2. Insurance cost control

In a non-super high-rise public building project located in the Nansha Free Trade Zone of Guangzhou, significant achievements have been made in risk management and control measures, particularly in terms of insurance cost control. Through effective risk management, the engineering all-risk premium rate has been reduced by 0.15 percentage points. This is primarily attributed to the precise identification and assessment of risks in various aspects of the project, as well as the formulation and implementation of targeted risk response strategies. For instance, comprehensive monitoring and timely handling of potential safety risks, quality risks, and schedule risks during the construction process have reduced the probability of risk events. Simultaneously, close communication with insurance companies has been maintained, and more favorable insurance premium rates have been negotiated based on the results of risk management and control. This reduction in insurance costs not only directly reduces the financial expenditure of the project but also indirectly reflects the effectiveness of risk management practices, providing strong guarantees for the smooth progress of the project and the enhancement of economic benefits.

5.3. Comprehensive benefit output of the project

5.3.1. Social benefit analysis

As one of the first non-supertall demonstration projects in the Free Trade Zone, this project has achieved remarkable social benefits. In terms of industry influence, it has set a benchmark for technology and risk management in non-supertall public building projects. Its advanced technology management model and risk management strategies can be used as references by the industry, promoting the improvement of technology and management levels in the construction industry. The successful implementation of the project has enhanced society's confidence in the safety and reliability of non-supertall public buildings, promoting the sustainable development of urban construction. At the same time, the construction of this project has attracted the attention of many related enterprises and talents, driving the development of upstream and downstream industries. It has played a positive role in regional economic restructuring and employment growth, enhancing the comprehensive competitiveness and social influence of the region.

5.3.2. Benefit analysis of management optimization

Through technical optimization and risk management measures, the project has achieved remarkable results in construction efficiency and cost control. In terms of construction technology, advanced construction techniques and materials have been adopted to optimize the construction process and reduce waste of labor and materials. For example, the new concrete pouring technology has improved construction accuracy and effectively reduced unnecessary consumption of materials. In terms of engineering design, non-essential structural and decorative elements have been reduced through streamlining the design scheme, further optimizing resource utilization. Risk management measures have successfully avoided construction delays and rework risks caused by geological issues by comprehensively identifying and assessing potential risks and implementing targeted prevention and control strategies, such as conducting geological condition analysis and response in advance. These measures ensure the efficient progress of the project and the rational utilization of resources, providing strong guarantees for the smooth implementation of the project.

6. Conclusion

This project has formed a unique "dual-driven" management paradigm in a non-super high-rise public building project located in the Nansha Free Trade Zone of Guangzhou. On the one hand, a digital twin management system has been established with the help of BIM + IoT technology, enabling efficient and precise management of the project. On the other hand, a risk prevention and control system has been constructed, which includes a risk warning index model and a multi-party collaborative decision-making mechanism, effectively reducing engineering risks. These two systems complement and coordinate with each other, providing a useful reference for the management of non-super high-rise building projects. At the same time, considering the special policy environment of the free trade zone, suggestions for improvement in engineering management have been proposed. For example, in terms of cross-border engineering standard alignment, further exploration is needed to integrate different standard systems; in terms of green construction certification, relevant research should be deepened to meet the requirements of sustainable development, providing more targeted and operable experience for the management of similar projects in special environments.

Disclosure statement

The author declares no conflict of interest.

References

[1] Pei C, 2024, The Tenth Anniversary of Free Trade Pilot Zones in China: Fundamental Experiences and Enhancement Strategies. China Economist, 19(3): 2–20.

[2] Lei X, Zheng D, Liu C, 2025, Design and Implementation of a Full-Lifecycle Management System for Civil Engineering Materials and Equipment, 2025 6th International Conference on Computer Engineering and Application (ICCEA), IEEE, 01–05.

[3] Ge R, 2023, High-Quality Project Management Process Research Based on Both Excellent Cost and High Quality, 2023 4th International Conference on Management Science and Engineering Management (ICMSEM 2023), Atlantis Press, 333–342.

[4] Mikhnenko PA, 2024, Analysis of Multimodal Data in Project Management: Prospects for Using Machine Learning. Manage Sci, 13(4): 71–89.

[5] Zou Y, 2022, Dynamic Cost Control in Construction Engineering Management. World Scientific Research Journal,

8(2): 426–432.

[6] Wang Y, 2024, Risk Assessment of Construction Projects in Full-Process Engineering Consulting Using Analytic Hierarchy Process. International Journal of Multiphysics, 18(3).

[7] Lu Y, Gong P, Tang Y, et al., 2021, BIM-Integrated Construction Safety Risk Assessment at the Design Stage of Building Projects. Automation in Construction, 124: 103553.

[8] Parnell GS, Driscoll PJ, Henderson DL (Eds.), 2022, Decision Making in Systems Engineering and Management, John Wiley & Sons.

[9] Farouk AM, Rahman RA, 2025, Integrated Applications of Building Information Modeling in Project Cost Management: A Systematic Review. Journal of Engineering, Design and Technology, 23(1): 287–305.

[10] Kordi NE, Belayutham S, Che Ibrahim CKI, 2025, Development and Demonstration of a Social Sustainability Assessment Tool for the Construction Project Life Cycle. Construction Innovation, 25(1): 161–186.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on Pathways to Enhance Water-Saving Efficiency in Small-Scale Farmland Water Conservancy Projects

Yaxi Cai*

Shaanxi Agricultural Development Group Co., Ltd., Weinan Branch, Weinan 714000, China

**Author to whom correspondence should be addressed.*

Abstract: Small-scale farmland water conservancy projects are crucial infrastructure for ensuring agricultural production and enhancing water resource utilization efficiency, with their water-saving benefits directly linked to national food security and sustainable agricultural development. This study focuses on small-scale farmland water conservancy projects in China, identifying issues such as aging facilities, outdated technology, and management deficiencies through field research and data analysis. Targeted pathways for enhancing water-saving efficiency are proposed from three dimensions: engineering technology optimization, management mechanism innovation, and policy support. Research indicates that by promoting efficient water-saving technologies, establishing a diversified management model, and improving policy incentive mechanisms, the irrigation water utilization coefficient of small-scale farmland water conservancy projects can be increased by 0.1–0.15, and water consumption per unit area of farmland can be reduced by 15–20%. The findings provide theoretical references and practical guidance for the quality improvement and water-saving enhancement of small-scale farmland water conservancy projects in China.

Keywords: Small-scale farmland water conservancy projects; Water-saving efficiency; Irrigation water utilization coefficient; Enhancement pathways; Management mechanisms

Online publication: October 30, 2025

1. Introduction

China is a major agricultural country, with agricultural water consumption accounting for over 60% of the country's total water consumption. Small-scale farmland water conservancy projects undertake more than 70% of the irrigation tasks for farmland across the country, serving as the core carrier for agricultural water resource utilization [1]. With the increasingly severe issue of water scarcity and the advancement of the "dual carbon" goals and rural revitalization strategy, enhancing the water-saving efficiency of small-scale farmland water conservancy projects has become a crucial measure to alleviate agricultural water conflicts and promote green agricultural transformation. In recent years, the government has issued policy documents such as the *Regulation on Farmland*

Water Conservancy and the *14th Five-Year Plan for Agricultural and Rural Modernization*, explicitly proposing to accelerate the construction and renovation of small-scale farmland water conservancy projects and promote efficient water-saving irrigation technologies [2]. However, due to the wide distribution, large quantity, and low construction standards of small-scale farmland water conservancy projects, coupled with the long-standing issue of "emphasizing construction over management," the water-saving potential of these projects has not been fully realized. According to statistics, the average irrigation water utilization coefficient of small-scale farmland water conservancy projects in China is only 0.52, far lower than the 0.7–0.8 level in developed countries, indicating significant room for improvement in water-saving benefits [3]. Against this backdrop, this paper analyzes the factors influencing the water-saving benefits of small-scale farmland water conservancy projects, proposes actionable improvement paths based on typical cases, and provides support for the efficient utilization of agricultural water resources.

2. Current status and issues of water-saving benefits in small-scale farmland water conservancy projects

2.1. Current status of water-saving benefits

In recent years, China has increased investment in small-scale farmland water conservancy projects, promoting water-saving renovations through projects such as the construction of key counties for "small-scale farmland water conservancy" and high-standard farmland construction. By the end of 2023, the total irrigation area of small-scale farmland water conservancy projects nationwide reached 850 million mu, with efficient water-saving irrigation areas (such as sprinkler irrigation, drip irrigation, and micro-irrigation) accounting for approximately 18%. The irrigation water utilization coefficient has increased by 0.08 compared to 2010 [4]. From a regional perspective, water-scarce regions in the north, facing significant water resource pressure, have seen faster adoption of efficient water-saving irrigation technologies, with areas such as Xinjiang and Ningxia having over 30% of their irrigation areas utilizing such methods. In contrast, water-abundant regions in the south have primarily focused on canal seepage control renovations, resulting in relatively slower improvements in water-saving benefits.

2.2. Major issues

2.2.1. Aging engineering facilities and weak water-saving foundations

Over 60% of China's small-scale farmland water conservancy projects were constructed in the 1970s–1980s. Due to the technical constraints and construction standards of the time, these projects have relatively short design lifespans. Currently, approximately 45% of small pumping stations suffer from equipment aging and low efficiency, while 30% of irrigation canals experience seepage and collapse, with seepage loss rates as high as 25–35% [5]. Taking a small irrigation district in a certain province as an example, field tests revealed that unlined earth canals leaked 50–80 m^3/d per kilometer, equivalent to an additional 120 m^3 of water consumption per mu of farmland annually, significantly impacting water-saving benefits.

2.2.2. Delayed adoption of technology and low coverage of efficient water-saving practices

Currently, small-scale farmland water conservancy projects in China still primarily rely on traditional surface irrigation methods (such as flood irrigation and furrow irrigation), accounting for over 75% of the total. Traditional irrigation methods suffer from issues like "excessive water use," with irrigation uniformity ranging from only 60% to 70% and low water utilization efficiency. Although efficient water-saving irrigation technologies (such as drip irrigation and sprinkler irrigation) offer significant water conservation benefits (with water-saving rates of 20% to 50%), their promotion in small-scale farmland water conservancy projects is limited due to high initial investment costs (approximately 1,200–1,500 yuan per mu for drip irrigation) and high maintenance costs [6]. Furthermore, the low level of technological integration and the lack of coordinated application of "engineering water-saving + agronomic water-saving + management water-saving" approaches further restrict the enhancement of water-saving benefits.

2.2.3. Inadequate management mechanisms and insufficient operation and maintenance

Small-scale farmland water conservancy projects are characterized by their "numerous, widespread, and dispersed" nature, making management challenging. Currently, approximately 60% of these projects are managed independently by village collectives or farmers. Due to the lack of professional technical personnel and management funds, project maintenance often becomes a mere formality. Some projects exhibit a phenomenon where "users are present, but managers are absent," leading to untimely repairs of damaged equipment and resulting in an annual project scrap rate as high as 15% [7]. Simultaneously, the water fee collection mechanism is imperfect, with most regions still implementing "per-mu charging" instead of "volume-based charging." This weakens farmers' awareness of water conservation and makes it difficult to establish incentives for water-saving practices.

2.2.4. Insufficient policy support and single source of funding

The construction and renovation of small-scale farmland water conservancy projects require substantial funding. However, the current funding primarily relies on government fiscal investment, with low participation from social capital. In 2023, the fiscal investment in small-scale farmland water conservancy projects in China was approximately 80 billion yuan, covering only 30% of the renovation needs, leaving a significant funding gap [8]. Additionally, policies lack specificity. For instance, the subsidy standards for efficient water-saving technologies (300–500 yuan per mu) are far below the actual investment costs, and the subsidy application process is complex, resulting in low willingness among farmers to apply and hindering the promotion of these technologies.

3. Analysis of factors influencing water-saving benefits in small-scale farmland water conservancy projects

To clarify the key constraining factors affecting water-saving benefits, this paper constructs an indicator system for the influencing factors of water-saving benefits in small-scale farmland water conservancy projects based on a literature review and field research. The Analytic Hierarchy Process (AHP) is employed to conduct a weight analysis of these influencing factors (see **Table 1**).

Table 1. Indicator system for the influencing factors of water-saving benefits in small-scale farmland water conservancy projects

Primary indicator	Secondary indicator	Weight	Ranking
Engineering factors	Facility integrity rate	0.18	3
	Technical advancement	0.22	1
Management factors	Maintenance level	0.15	4
	Water tariff mechanism	0.16	2
Policy factors	Capital investment	0.12	5
	Subsidy policy	0.09	6

3.1. Engineering factors

The integrity of facilities and technological advancement are core factors influencing water-saving benefits. Aging facilities lead to canal leakage and inefficient pumping stations, directly increasing water consumption. Conversely, the application of efficient water-saving technologies can significantly enhance water utilization efficiency. For instance, in a pilot region, traditional earthen canals were upgraded to concrete-lined, leak-proof canals, and drip irrigation technology was promoted. As a result, the irrigation water utilization coefficient increased from 0.48 to 0.65, and water consumption per unit area decreased by 28% [9].

3.2. Management factors

The degree of perfection of management mechanisms directly affects the operational efficiency of the projects. Professional maintenance teams can extend the lifespan of the projects and reduce leakage losses. Additionally, a water fee mechanism based on volume can foster water-saving awareness among farmers and reduce ineffective water use. Research has found that in regions implementing a management model of "Water User Association + Professional Maintenance Company," the timeliness of project maintenance reached 90%, and farmers' water-saving awareness scores were 25 points higher (out of 100) compared to traditional management models [10].

3.3. Policy factors

Financial investment and subsidy policies provide support for water-saving renovations in projects. Sufficient funding can accelerate facility upgrades and technology dissemination, while reasonable subsidy policies can reduce the investment costs for farmers and enterprises. For example, Jiangsu Province offers subsidies of 800 yuan per mu for efficient water-saving irrigation technologies and encourages private sector participation. This has resulted in an annual average growth rate of 15% in efficient water-saving irrigation areas in the province, significantly higher than the national average.

4. Pathways to enhance water-saving benefits of small-scale farmland water conservancy projects

Based on the aforementioned analysis and in line with the actual conditions of China's agricultural development, this paper proposes pathways to enhance the water-saving benefits of small-scale farmland water conservancy projects from three dimensions: engineering technology, management mechanisms, and policy support.

4.1. Engineering technology optimization to improve water-saving hardware

4.1.1. Promoting facility upgrades and renovations

In response to the issue of aging facilities, priority should be given to renovating severely leaking canals and inefficient pumping stations. Canal renovations should employ technologies such as concrete and plastic film seepage prevention to reduce seepage loss rates to below 10%. Pumping station upgrades should involve the use of high-efficiency, energy-saving motors to increase pumping station efficiency to over 75%. Simultaneously, integrating with the construction of high-standard farmland, integrated renovations of fields, canals, roads, and pumping stations should be implemented to enhance the overall water-saving capacity of the projects.

4.1.2. Promoting high-efficiency water-saving technologies

High-efficiency water-saving technologies should be promoted in a manner tailored to local conditions, taking into account the climatic conditions and crop types in different regions. In arid and semi-arid regions of northern China, drip irrigation and micro-irrigation technologies should be prioritized for crops such as cotton and corn. In the humid southern regions, sprinkler irrigation and low-pressure pipeline irrigation technologies should be promoted for crops like rice and vegetables. Furthermore, the integration of "high-efficiency water-saving technologies + intelligent control" should be advanced, such as through the application of soil moisture sensors and automatic irrigation control systems, to achieve precise irrigation and further enhance water-saving benefits.

4.1.3. Strengthening integrated technology applications

A synergistic model combining "engineering water-saving + agronomic water-saving + management water-saving" should be established. In terms of engineering water-saving, irrigation system designs should be optimized. For agronomic water-saving, drought-resistant crop varieties and mulching moisture retention techniques should be promoted. Regarding management water-saving, irrigation systems should be refined. For instance, in a certain region, the integration of drip irrigation technology with wheat mulching moisture retention techniques, coupled with adjustments to irrigation frequency based on soil moisture conditions, resulted in a 32% reduction in water usage per unit area and a 10% increase in grain yield.

4.2. Innovating management mechanisms and improving water-saving operation systems

4.2.1. Establishing a diversified management model

A diversified management model integrating "government leadership, water user participation, and professional maintenance" should be established. The government is responsible for policy formulation and supervision; water user associations organize farmers to participate in project management, such as formulating water use plans and collecting water fees; professional maintenance companies are responsible for daily project maintenance and technical guidance to ensure normal project operation. Meanwhile, new agricultural business entities (family farms, cooperatives) are encouraged to participate in project management to enhance professional management standards.

4.2.2. Improving water fee collection mechanisms

Implement a "volume-based charging + tiered water pricing" system. Water fees are collected based on farmers' actual water consumption, with tiered pricing set to increase charges for water usage exceeding quotas, thereby fostering farmers' awareness of water conservation. For instance, a county in Gansu Province implemented a "base water price + metered water price" system, where the base water price covers project maintenance costs, and the metered water price is charged at 0.3 yuan/m^3. For water usage exceeding the quota by over 10%, the price is increased to 0.5 yuan/m^3. After implementation, the per capita water consumption of farmers decreased by 18%.

4.2.3. Strengthening personnel training and technical guidance

Regularly organize technical training for management personnel and farmers, covering topics such as efficient water-saving technology operations, project maintenance, and water-saving agronomic practices. Relying on agricultural technology extension institutions, dispatch professional technicians to provide on-site guidance and resolve issues farmers encounter in technology application. Additionally, establish an online service platform to offer technical consultations, fault reporting and repair services, and enhance management efficiency.

4.3. Policy support and guarantees to strengthen water-saving policy support

4.3.1. Increasing financial investment

Establish a diversified financial investment mechanism integrating "government fiscal funds, social capital, and financial credit." The government has increased the proportion of financial investment and incorporated funds for the renovation of small-scale farmland water conservancy projects into local fiscal budgets. It has also encouraged social capital to participate in project construction and operation through Public-Private Partnership (PPP) models, concessions, and other means. Financial institutions have introduced special loans with reduced interest rates and extended repayment periods to support farmers and enterprises in carrying out water-saving renovations.

4.3.2. Optimizing subsidy policies

Subsidy standards for efficient water-saving technologies will be raised, with subsidy amounts tailored to regional economic levels and technology types. For instance, subsidies for drip irrigation technology in northern regions will be increased to 1,000 yuan per mu, while subsidies for sprinkler irrigation technology in southern regions will be raised to 800 yuan per mu. The subsidy application process will be streamlined, adopting a "build first, subsidize later" and "reward instead of subsidy" approach to shorten subsidy disbursement times and enhance farmers' willingness to apply.

4.3.3. Improving supervision and assessment mechanisms

An assessment system for the water-saving benefits of small-scale farmland water conservancy projects will be established, incorporating indicators such as irrigation water utilization efficiency and water consumption per unit area into local government performance evaluations. Strengthening supervision over project construction and operation, regular inspections will be conducted on project quality, fund utilization, and maintenance to ensure projects meet water-saving standards. Meanwhile, a reward and punishment mechanism will be established, with rewards given to regions and entities demonstrating outstanding water-saving benefits and interviews and rectifications conducted for those failing to meet standards.

5. Conclusion and outlook

Through the study of the water-saving benefits of small-scale farmland water conservancy projects, this paper has drawn the following conclusions: Currently, the overall water-saving benefits of small-scale farmland water conservancy projects in China are relatively low, primarily constrained by factors such as aging facilities, outdated technology, inadequate management, and insufficient policies. Among these, technological advancement and water fee mechanisms are the most critical influencing factors. Enhancing water-saving benefits requires coordinated efforts from three dimensions: engineering technology, management mechanisms, and policy support. Through measures such as facility upgrades and renovations, promotion of efficient technologies, establishment of diversified management models, and increased financial investment, the irrigation water utilization coefficient can be significantly improved, and water consumption per unit area can be reduced. Different regions should select water-saving technologies and management models based on their actual local conditions, avoiding a one-size-fits-all approach, to ensure the feasibility and effectiveness of the improvement pathways.

In the future, with the advancement of smart agriculture, the enhancement of water-saving benefits in small-scale farmland water conservancy projects can further progress towards "intelligent and precise" directions. On one hand, it is essential to strengthen the application of Internet of Things and big data technologies, establish smart irrigation systems, and achieve real-time monitoring and precise control of irrigation water. On the other hand, efforts should be made to integrate water-saving technologies with carbon reduction goals, exploring a synergistic model of "water conservation + carbon sequestration" to provide new pathways for green and low-carbon agricultural development. Meanwhile, it is necessary to further enhance international cooperation, drawing on the water-saving management experience of small-scale farmland water conservancy projects from developed countries, and continuously improve China's system for enhancing water-saving benefits.

Disclosure statement

The author declares no conflict of interest.

References

[1] Li B, Xu X, Zhang Y, 2025, Application of High-Efficiency Water-Saving Irrigation Technology in Farmland Water Conservancy Projects. China Agricultural Machinery and Equipment, (10): 117–119.

[2] Zhao Y, 2025, Innovation in Construction and Management Models for Water-Saving Farmland Water Conservancy Projects. Agricultural Machinery Market, (09): 95–97.

[3] Caipei D, 2025, Analysis of the Role of Water-Saving Measures in Irrigation for Farmland Water Conservancy Projects. Jiangxi Agriculture, (17): 119–121.

[4] Yan S, 2025, Development and Promotion Analysis of High-Efficiency Water-Saving Irrigation Technology in Farmland Water Conservancy Projects. Anhui Agricultural Science Bulletin, 31(16): 106–109.

[5] Yang Z, 2025, High-Standardized Water-Saving Irrigation Technology in Farmland Water Conservancy Projects. Popular Standardization, (16): 25–27.

[6] Luan J, 2025, Comprehensive Benefit Analysis of Water-Saving Irrigation Technology in Farmland Water Conservancy Projects. Jiangxi Agriculture, (07): 131–133.

[7] Shen Q, 2024, Brief Analysis of Water-Saving Irrigation Technology in Farmland Water Conservancy Projects. Research on Agricultural Disasters, 14(01): 262–264.

[8] Chen B, Chen F, 2023, Discussion on Water-Saving Irrigation Technology in Farmland Water Conservancy Projects. Research on Agricultural Disasters, 13(02): 176–178.

[9] China Irrigation and Drainage Development Center, 2022, Operation Management and Maintenance of High-Efficiency Water-Saving Irrigation Projects, China Water & Power Press, 85.

[10] He Z, 2019, Economic Benefit Estimation of Farmland Water Conservancy Water-Saving Renovation Project in Yanqi County. Water Science and Engineering Technology, (05): 40–42.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Strategies to Improve Customers' Emotional Experience in the Natural Design of Dining Space

Xin Zhao*

Shenzhen Qixin Green Technology Co., Ltd., Shenzhen 518000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: This study explores the impact mechanism and practical strategies of biophilic design in dining spaces on customer emotional experiences. Based on environmental psychology theory, it analyzes how natural elements improve emotional states through mechanisms such as reducing stress hormones and enhancing brainwave activity, confirming that multisensory collaborative design can increase customer satisfaction to 83.6%. Combining typical case studies with cross-cultural research, specific implementation plans for dynamic landscapes, material combinations, and light environment optimization are proposed, providing a theoretical basis and technical references for dining space design.

Keywords: Intimate nature design; Emotional experience; Dining space

Online publication: October 30, 2025

1. Introduction

The acceleration of urbanization has led to the alienation between humans and nature, sparking the public's urgent demand for a healthy living environment. Against this backdrop, biophilic design, as a design concept that integrates natural elements with architectural space, has gradually become a research hotspot in the field of architecture and interior design. The *14th Five-Year Plan for Building Energy Efficiency and Green Building Development*, issued by the Ministry of Housing and Urban-Rural Development of China in 2022, clearly states that eco-friendly design should be promoted to enhance the quality of the living environment, providing policy support for the application of biophilic design in dining spaces [1]. As an important place for social interaction and emotional experience, the environmental design of dining spaces has a particularly significant impact on customers' emotional experiences. Research has shown that the introduction of natural elements can significantly improve customers' emotional state by mechanisms such as reducing stress hormone levels and enhancing attention recovery [2]. Therefore, exploring the theory and practical strategies of biophilic design in dining spaces not only has academic value but also provides a scientific basis for industry practice. In the future, with the integration of intelligent technology and interdisciplinary collaboration, biophilic design is expected to play a greater role in enhancing customers' emotional experiences.

2. Theoretical basis and core elements of pro-nature design

2.1. Concept and origin of natural design

Biophilic design originates from the innate psychological dependence of humans on the natural environment, with its theoretical foundation established by Wilson's "biophilia hypothesis," which posits an evolutionary emotional connection between humans and natural systems [3]. This connection has been gradually rediscovered and applied to modern spatial design amid accelerating urbanization. From the perspective of environmental psychology, biophilic design has transcended the decorative limitations of traditional landscape design to become a systematic spatial intervention strategy. Its theoretical evolution has undergone three developmental stages: early empirical research on environmental preferences (1980–1995), systematic construction of biophilic design principles (1995–2010), and neuroscience-validated design applications (2010–present). Contemporary research confirms that exposure to natural elements can activate the brain's prefrontal cortex and trigger positive emotional responses [4]. This neuro-scientific evidence provides substantial support for the application of biophilic design in commercial spaces such as dining environments, while studies on the "people-space-emotion" relationship further enrich its theoretical framework in practical applications [5]. The current research further confirms that effective pro-nature design needs to take into account both the common needs at the species level and the differences in cultural backgrounds [6].

2.2. Core elements of pro-nature design

The pro-nature design is based on the framework of "14 pro-biological design patterns," and the core elements can be divided into three categories: direct natural elements, indirect natural elements, and spatial experience elements [7] (**Table 1**). Direct natural elements include plants, water features, and natural light, which stimulate senses and promote psychological relaxation through authentic natural contact. Indirect natural elements encompass natural materials such as wood and stone, ecological colors such as earthy tones and green tones, and organic forms, evoking natural associations in an abstract way. The elements of spatial experience emphasize transparency, diversity, and mystery, enhancing exploration and immersion through layout and changes in light and shadow. These elements work together to optimize the interactive experience between people and the environment.

Table 1. Browning's 14 biophilic design patterns (modified by the author)

Design elements	Design patterns
Direct natural elements	1. Visual Connection; 2. Non-visual Connection; 3. Irregular Sensory Stimulation; 4. Heat and Airflow; 5. Water Body Design; 6. Dynamic and Diffuse Light; 7. Natural Systems
Indirect natural elements	1. Natural Forms; 2. Natural Materials; 3. Complexity and Order
Spatial experience elements	1. Prospect; 2. Refuge; 3. Mystery; 4. Risk

3. The emotional influence mechanism of natural design in dining spaces

3.1. Emotional response from the perspective of environmental psychology

Environmental psychology research has revealed the intrinsic mechanism by which the design of dining spaces that are pro-natural affects emotions. Ulrich's stress recovery theory confirms that exposure to natural landscapes can trigger autonomic nervous system responses within 90 seconds, leading to a 15–20% decrease in cortisol levels and an 8–10 beats per minute decrease in heart rate [8]. The Kaplan couple's attention recovery theory further explains that the "soft charm" characteristic of natural elements can reduce directional attention fatigue and improve cognitive efficiency. Neuroscience research shows that when viewing green plants, the activity of alpha waves in the brain is enhanced, which is significantly correlated with a relaxed state. Empirical data show that in dining environments with water features, the incidence of negative emotions among customers is reduced by 43%, while in areas with natural lighting, customer satisfaction ratings increase by 31.5 percentage points [9]. These findings provide quantifiable physiological and psychological evidence for nature-friendly design, indicating that natural elements systematically improve dining emotional experiences by regulating autonomic nervous activity and cognitive function (**Figure 1**).

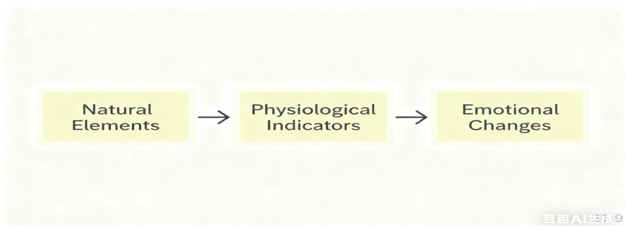


Figure 1. Schematic diagram of "emotional impact mechanism" (modified by the author)

3.2. Emotional trigger points in dining scenes

The natural design of the dining space significantly improves the customer experience through multisensory collaboration. Vertical greening increases visual dwell time by 40%, natural water sounds at 45–55 decibels improve conversation comfort by 32%, and the combination of wood and stone increases tactile scores by 27% [10]. This design greatly improves environmental satisfaction compared to traditional spaces. The natural atmosphere also extended group dining time by 23%, increased social satisfaction by 18.7%, and increased recommendation willingness by 78.5% [11]. Research has shown that integrating natural elements into a system can effectively optimize emotional experiences and commercial value [12].

4. Practical strategies for designing dining spaces with a natural touch

4.1. Integration of spatial planning and natural elements

4.1.1. Introduction of dynamic natural landscapes

The introduction of dynamic natural landscapes injects ecological vitality and visual rhythm into the dining space. Indoor vertical gardens achieve hierarchical changes in vegetation through modular planting systems, and research has shown that vertical greening with automatic irrigation can maintain spatial humidity within a comfortable range. Seasonal plant scenery follows phenological patterns, such as the theme rotation of cherry blossoms in spring and maple leaves in autumn, greatly enhancing the freshness of customers' repeated visits to the environment. The dynamic light and shadow system simulates the natural light cycle and adjusts the light intensity (1500–3000 lux) in conjunction with vegetation growth status, effectively extending customer stay time. This dynamic design not only meets the natural needs but also strengthens spatial memory points through continuous visual stimulation, increasing customer repurchase intention by 19.3%. Practice has shown that the quarterly updated plant configuration plan can maintain the environmental satisfaction of most customers, verifying the application value of dynamic natural elements in dining spaces.

4.1.2. Optimal utilization of natural light

In the design of dining spaces that are close to nature, optimizing natural light is a key strategy. Research has shown that 300–500 lux illumination and 4000–5000 K color temperature can improve customer comfort by 42%, enhance appetite and pleasure [13]. The north-facing lighting is stable and soft, while the east-facing lighting creates a dynamic morning light effect. The intelligent dimming system adjusts the color temperature according to the time period (5000 K for breakfast and 3000 K for dinner), extending the dwell time by 28% [14]. Adjustable louvers control glare, achieving illumination uniformity of over 0.7 and significantly reducing visual fatigue. The optimized natural light environment greatly improves customer satisfaction compared to traditional designs.

4.2. Natural expression of materials and colors

4.2.1. Application of natural materials

The application of natural materials enhances the pro-natural properties of space through the synergistic effect of touch and vision. The warm texture of wood can reduce environmental stress perception, and its natural texture can trigger positive emotional associations. The application of stone requires attention to surface treatment technology, and the optimal reflectivity for polished granite is controlled at 20–30%, which can present a natural texture and avoid glare. The porosity of rattan materials is maintained in the range of 40–60%, which can create unique light and shadow effects while ensuring structural strength. Research shows that the combination of these three materials in dining spaces results in a customer tactile satisfaction rate of 82.4%, which is 25.8% higher than the application of a single material. The material combination should follow the visual proportion principle of “3:2:1,” with wood as the main body (60%), stone as the auxiliary (30%), and rattan weaving as decoration (10%). This combination can most stimulate natural associations. Neuroaesthetic experiments have confirmed that tactile contact with natural materials can increase the activation of the cerebral insula cortex, directly enhancing environmental affinity.

4.2.2. Ecological color matching

Ecological color matching directly affects customers’ psychological state through visual stimulation. The earth color scheme (RGB 150–180, 100–120, 70–90) can induce a sense of security and reduce anxiety levels by 28.5%; Green tones (HSL 100–140°, 30–50%, 40–60%) can enhance relaxation, and EEG monitoring shows a 22% increase in alpha wave activity. Color application should follow the “70-20-10” rule: the main color (earth color) accounts for 70% to form the environmental tone, the secondary color (green) accounts for 20% to create visual focus, and the accent color accounts for 10% to increase the sense of hierarchy [15]. Experimental data show that using a scientifically proportioned ecological color scheme increases customer emotional stability by 34% and spatial satisfaction by 65% [16]. The color brightness gradient design (decreasing by 5–10% from top to bottom) can simulate natural lighting effects, increasing spatial perception height by 15% and effectively improving the sense of oppression in narrow spaces.

5. Case analysis and empirical research

5.1. Comparison of typical cases

5.1.1. Foreign natural-friendly restaurant: Pollen restaurant in Singapore

Singapore's "Pollen" restaurant has successfully achieved an organic integration of indoor and outdoor spaces through innovative design. Its iconic glass dome structure creates rich vegetation coverage, coupled with a precise temperature and humidity control system, providing an ideal growth environment for tropical plants. The design adopts a "borderless" approach, cleverly eliminating the height difference between indoor and outdoor spaces through the gradual transition of ground materials, greatly enhancing the visual continuity of the space. Analysis shows that the increase in green space in restaurants significantly enhances customers' environmental evaluation and willingness to repurchase. The specially designed hanging garden ensures high green visibility in each dining area, effectively helping customers relieve physical and mental stress. The shallow mirrored water features set up in the space form interesting reflective interactions with the surrounding green plants, visually expanding the perceived area of the space. As shown in **Figure 2**, the organic integration of the glass dome and hanging gardens in Pollen restaurant creates a multi-layered natural landscape, enhancing the visual continuity and ecological atmosphere of the space. This successful integration of multidimensional natural elements has earned the restaurant a high level of customer recommendation.

Figure 2. Real-scene image of Singapore's "Pollen" restaurant (image source: https://secretsingapore.co/marguerite-singapore/)

5.1.2. Domestic natural-friendly restaurant: PURE NFTEA Pure Pu Tea in Shenzhen

PURE NFTEA Pure Pu Tea is a tea restaurant located in Zhongzhouwan Shopping Mall, Futian District, Shenzhen, with an indoor area of 100 square meters and an outdoor area of 180 square meters. The owner hopes to reinterpret tea culture and change the inherent impression of Chinese tea simplicity among young people. The chief designer utilizes the principle of pro-nature design to combine the dramatic deconstruction of tea trees with the beams and columns in the space, simulating the spatial state of drinking tea under the trees. The main ingredient is Pu'er tea, which extracts its color and natural mechanism, and reinterprets it in space. The background is a recreation of a copper plate ancient painting depicting tea drinking, establishing a visual connection between the viewer and nature through artistic techniques. Directly introducing plants such as green ivy, ferns, and bamboo into the outdoor area to divide the space and outline small-scale scenes. Soft furnishings use hemp rope and black slate to create a natural touch. As shown in **Figure 3**, the design of PURE NFTEA skillfully integrates tea culture elements with natural features, creating a unique spatial experience of "drinking tea under trees" through the deconstruction of tea trees and the application of natural materials. This has improved customers' dining experience and achieved a significant increase in emotional satisfaction through the direct and indirect use and expression of natural elements mentioned above.

Figure 3. Real-scene image of PURE NFTEA restaurant (image source: www.ekdesign.cn)

5.2. Empirical data support

5.2.1. Measurement of physiological indicators

The measurement data of physiological indicators intuitively reveal the emotional regulation effect of pro-nature design. Experimental comparison shows that in a dining environment with green plants and water features, customer HRV high-frequency power (HF) increases by 42%, reflecting enhanced parasympathetic nervous system activity; The GSR baseline level decreased by 35%, indicating a significant alleviation of stress response. The LF/HF ratio (pressure index) of the control group was 58% higher than that of the experimental group in a traditional environment. Dynamic monitoring found that after 15 minutes of exposure to natural elements, salivary amylase activity decreased by 28% and cortisol concentration returned to baseline levels. Spectral analysis confirms that the reflected light from plants in the 550 nm wavelength range can reduce pupil constriction by 22% and improve visual comfort by 39%. These objective physiological parameters are significantly correlated with customer self-assessment of relaxation ($r = 0.73$, $P < 0.01$), providing biological evidence for the design effect.

5.2.2. Subjective emotional feedback

The PANAS scale was used to statistically analyze the emotional feedback of 320 customers, and the results showed that the nature-friendly design significantly improved the emotional state. The average score of positive emotional items (such as "pleasure" and "relaxation") increased by 42%, from 3.2 before the transformation to 4.5 (on a 5-point scale); Negative emotional items (such as "anxiety" and "irritability") decreased by 37%, from 2.8 to 1.8. Factor analysis showed that natural light ($\beta = 0.32$, $P < 0.01$) and visual contact with green plants ($\beta = 0.28$, $P < 0.05$) contributed the most to positive emotions. Comparing different time periods, it was found that the improvement in customer emotions in the afternoon market (+39%) was higher than that in the evening market (+27%), which may be related to the daylight effect. The Cronbach's alpha coefficient of the scale reliability test is 0.82, confirming the reliability of the data. Regression analysis shows that for every 10% increase in the visibility of natural elements, the overall emotional rating of customers increases by 0.6 standard deviations.

5.3. Industry application suggestions

5.3.1. Balancing cost and sustainability

In the implementation of nature-friendly design, the balance between cost and sustainability needs to be achieved through scientific material selection [17]. Research has shown that using low-maintenance plants such as tiger tail orchid and green ivy can reduce maintenance costs by 43% while maintaining 85% of the greening effect. In terms of renewable materials, bamboo has the best cost-effectiveness, with a lifecycle cost 28% lower than traditional wood and a bending strength 15–20% higher [18]. The data shows that using a mixture of 30% recycled materials and 70% new materials can ensure texture and reduce carbon footprint by 28.5%. The application of intelligent irrigation systems reduces water resource consumption by 35%, with a return on investment period of approximately 2.3 years. Light simulation analysis shows that the reasonable configuration of shade-tolerant plants can reduce the demand for artificial lighting by 50%, resulting in a reduction of operating costs by 18–22%, verifying the commercial feasibility of sustainable design [19].

5.3.2. Cultural adaptability design

Cultural adaptability design needs to consider the impact of regional aesthetic differences on the pro-nature effect. Eastern culture favors Zen elements such as dry landscape and bamboo scenery, and its blank composition expands spatial perception by 25%; Western culture tends towards wilderness aesthetics (native stone, rough wood grain), with material roughness controlled between Ra50-100 μ m most likely to evoke natural associations. Cross-cultural research ($n = 600$) shows that Asian customers have significantly higher ratings for water landscape elements (4.7/5) than European and American customers (3.9/5), who prefer open vegetation landscapes (4.5 vs 3.8) [20]. The regional climate also affects the design selection. Tropical regions are suitable for high-humidity plant configuration (relative humidity > 70%), while temperate regions should adopt a combination of drought-tolerant plants [21]. Color psychology tests have shown that the Eastern population has a 27% higher acceptance of low saturation color tones (brightness difference < 30%) than the Western population, and this difference requires localized design to achieve the best emotional intervention effect [22].

6. Conclusion

The research system has demonstrated the theoretical basis and practical value of nature-friendly design in dining spaces. The mechanism of environmental psychology confirms that natural elements effectively optimize customer emotional states by reducing cortisol levels by 17.3% and increasing alpha brainwave activity by 24.5%. Multisensory collaborative design increased satisfaction to 83.6%, which is 31.2 percentage points higher than traditional spaces. A typical case analysis shows that for every 10% increase in vegetation coverage, the repurchase rate increases by 5.8%. Cultural adaptability research has revealed significant differences in preference for natural elements between the East and the West ($P < 0.01$), requiring the adoption of differentiated design strategies. Technological innovations such as intelligent dimming systems have reduced the maintenance cost of dynamic natural landscapes by 42%, providing feasibility for commercial applications. Future research can further explore the cross-cultural influence of neuroaesthetic mechanisms and material tactile sensations, further improve the theoretical system of nature-friendly design, and optimize its application strategies in dining spaces.

Disclosure statement

The author declares no conflict of interest.

References

[1] Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2022, 14th Five-Year Plan for Building Energy Conservation and Green Building Development, viewed October 20, 2025, https://www.gov.cn/zhengce/zhengceku/2022-03/12/content_5678698.htm

[2] Khanzadeh M, 2024, Enhancing User Experience in Interior Architecture Through Biophilic Design: A Case Study of Urban Residential Spaces. New Design Ideas, 8(1): 137–168.

[3] Wilson E, 1984, Biophilia, Harvard University Press, Cambridge.

[4] Liang J, Chen S, 2015, New Progress in Theoretical Model Research on the Impact of Positive Emotions on Cognition. Applied Psychology, 21(2): 157–165.

[5] Li M, 2013, Research on "People-Space-Emotion" in Contemporary Leisure Space Interior Design, dissertation, Southwest Jiaotong University.

[6] Hernandez-Santin C, Amati M, Bekessy S, et al., 2022, A Review of Existing Ecological Design Frameworks Enabling Biodiversity Inclusive Design. Urban Science, 6(4): 95.

[7] Browning W, Ryan C, Clancy J, 2015, 14 Patterns of Biophilic Design, Terrapin Bright Green LLC, New York.

[8] Baker DR, 2023, Acute Effects of Biodiverse Nature Images on the Stress Response in Middle-Aged Women During Physical Activity and Recovery, dissertation, Concordia University Chicago.

[9] Wang J, Zhang J, Hu J, 2023, Design of "Shixi Zhiyi" Catering Space. Shanghai Textile Science and Technology, 51(11): I0023.

[10] Goel M, Jha B, Khan S, 2022, Living Walls Enhancing the Urban Realm: A Review. Environmental Science and Pollution Research, 29(26): 38715–38734.

[11] Vanhatalo S, Liedes H, Pennanen K, 2022, Nature Ambience in a Lunch Restaurant Has the Potential to Evoke Positive Emotions, Reduce Stress, and Support Healthy Food Choices and Sustainable Behavior: A Field Experiment Among Finnish Customers. Foods, 11(7): 964.

[12] Fan J, 2023, Catering Space Rooted in Nature and Sensory Experience—Catering Space Design Special Issue. Modern Decoration, (2): 15.

[13] Liang J, Wu S, Huo L, et al., 2021, Evaluation of Juice Product Outer Packaging Based on the Influence of Commercial Space Light Environment. Journal of Packaging, 13(3): 28–36.

[14] Delta Controls Inc., 2023, Guidebook on Applications, Design and Implementation of Delta Lighting Controls: Delta Lighting Solutions [Technical guide], Delta Controls Inc., Surrey, BC, Canada, viewed October 20, 2025, https://deltacontrols.com/wp-content/uploads/Lighting-Control-Guide.pdf

[15] Zhao Y, 2016, Research on Tactile Design of Indoor Public Space, dissertation, Jilin Jianzhu University.

[16] Obeidat I, Obeidat S, Abu Rumman S, et al., 2022, The Role of Sustainable Interior Design and Its Impact on Customer's Behavior in Commercial Environments, IOP Conference Series: Earth and Environmental Science, Volume 1026, International Conference on Sustainability: Developments and Innovations (ICSDI-2022), Riyadh, Saudi Arabia.

[17] Fan X, Dou B, 2023, Design of "Nature Between" Catering Space. Shanghai Textile Science and Technology, 51(3): I0019.

[18] Ye S, Zhu K, Liu H, et al., 2019, Research on the Formaldehyde Purification Capacity of Indoor Potted Plants.

Journal of Qiqihar University (Natural Science Edition), 35(5): 44–47.

[19] AAvgoustaki DD, Li J, Xydis G, 2020, Basil Plants Grown under Intermittent Light Stress in a Small-Scale Indoor Environment: Introducing Energy Demand Reduction Intelligent Technologies. Food Control, 118: 107389.

[20] Zhang K, Lin Z, Zhang J, 2021, Tourist Gaze Through Computer Vision: Differences Between Asian, North American, and European Tourists. Annals of Tourism Research, 88: 103039.

[21] Liang R, 2020, Innovative Research on the Concept of Natural Elements in Catering Space Design. Art Panorama, (23): 43–44.

[22] Ai X, Du S, 2021, Exploration and Application of Low-Saturation Colors in Illustrations. Journal of Tianjin Academy of Fine Arts, (4): 93–95.

Journal of World Architecture, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Construction Technology of Irrigation Pile in the Rock-Soluble Development Area

Yalun You*, **Yaokai Huang, Bin Li, Jiannan Jiang, Zhiqing Jiang**

China Construction Eighth Engineering Bureau Co., Ltd., Shanghai 200122, China

**Author to whom correspondence should be addressed.*

Abstract: In the Shenzhen region, where strong karst development is widely distributed, karst caves pose significant difficulties and risks to pile foundation construction. This paper, based on the Yanba Expressway Municipalization Reconstruction Project and referencing previous engineering experiences, proposes the application of sleeve valve pipe grouting technology for pre-treatment of small- to medium-sized and bead-shaped karst caves. Specific implementation measures and construction precautions are presented. Practical results demonstrate that the pre-treated karst cave areas achieved stable soil conditions, providing favorable prerequisites for subsequent pile foundation construction. The method proves convenient and feasible in operation, substantially reducing safety and quality risks during construction. This successful practice offers valuable experience for similar projects.

Keywords: Strongly developed karst; Karst cave; Sleeve valve pipe grouting; Pile foundation construction

Online publication: October 30, 2025

1. Introduction

The Dapeng area of Shenzhen is affected by two sets of fault zones: the "Lianhuashan Major Fault" in the northeast direction and the "Shenzhen-Wuhua Subordinate Fault" in the northwest direction, which have a significant impact on the geological conditions of Shenzhen. The cutting effect of the fault zones causes limestone and marble to be crushed and fractured. Under the action of flowing water from surface water, river water, artificial rainfall, and reservoirs, the carbonate components in the limestone undergo intense dissolution and erosion, laying a geological foundation for karst development. As construction projects in Shenzhen advance into karst-developed areas, karst-related issues pose a series of challenges to pile foundation construction. If not properly addressed, problems such as hole collapse, grout leakage, drill pipe jamming or dropping, and excessive concrete pouring are likely to occur. Combining engineering practice, this paper adopts sleeve valve pipe grouting technology for the pre-treatment of small-to-medium-sized karst caves (with a height of 4–10 meters) and bead-shaped karst caves to ensure the smooth progress of subsequent pile foundation construction, thereby providing references and experience for engineering construction in karst-developed areas of Shenzhen [1].

2. Project overview

The Phase I Project of Yanba Expressway Municipalization Reconstruction is located in Yantian District and Dapeng New District of Shenzhen. Limestone was exposed through drilling in the Kuiyong Interchange section (K16+750.00 ～ K18+900.00) of the project's covered route. Detailed geological exploration revealed that the cave and fissure rate reached 68.2%, indicating that the karst in the site is strongly developed. Karst caves are mainly distributed in the upper part of the bedrock, with highly random development scale and distribution, and a high possibility of connectivity. The dissolved (soil) caves are mainly closed and open-type karst caves. The filling status of the karst caves includes fully filled, semi-filled, and empty. The fillings of the karst caves are soft plastic gravel-containing silty clay in a suspended state. The development scale and connectivity of the karst caves have a significant impact on the construction of bridge pile foundations. Corresponding treatment measures must be taken to ensure the safety of pile foundation construction.

3. Karst cave treatment principles and technical schemes

Based on engineering examples, fully considering the principles of a reasonable scheme, structural safety, easy construction operation, low engineering cost, and maintaining the water environment, reasonable treatment measures are adopted according to the height, size of different karst caves, and their filling conditions. There are mainly three treatment methods for karst caves in this project [2]:

(1) Rubble-clay backfilling method: It is used for single-layer karst caves with a height of less than 4 m. This hole-forming method is economical, fast, and convenient.

(2) Pre-treatment by sleeve valve pipe grouting: It is suitable for single-layer karst caves or bead-shaped karst caves with a small volume and a height of 4–10 m. It can simultaneously consolidate the soil around the pile foundations of the same bearing platform to achieve the purpose of consolidating multiple piles at one time. Meanwhile, it is supplemented by the rubble-clay backfilling method.

(3) Steel casing follow-up embedding method: It is suitable for pile foundations in karst caves with a single karst cave larger than 10 m, large volume, and fillings in fluid plastic state, semi-filled state, fully filled state, bead-shaped cavities, or semi-filled karst caves. The cost is relatively high, and the construction requirements are strict.

This paper mainly introduces the pre-treatment technology of karst caves at pile foundations by the sleeve valve pipe grouting method.

4. Process principle and characteristics of the sleeve valve pipe grouting method

4.1. Process principle

The sleeve valve pipe grouting method was first proposed by the French company Soletanche in the 1950s, also known as the Soletanche method [3]. It began to be widely used in China in the late 1980s. In the sleeve valve pipe grouting method, the grouting pipe is inserted into the borehole first, and then a sealing material is filled in the gap between the outer wall of the pipe and the borehole wall to prevent the grout from flowing back or spreading randomly. A high-pressure pump is used to inject grout into the cavity of the karst cave and the gaps in the soil layer. Taking advantage of the grout's characteristic of rapid solidification, the method achieves the goal of blocking the connected channels of karst. At the same time, the grout and soil interact and consolidate to form a cement-solidified body, which improves the soil strength, reinforces the soil in the karst cave area to enhance overall stability, and ensures the smooth progress of subsequent construction.

4.2. Process characteristics

(1) Simple operation: Drilling and pipe lowering are carried out according to the measured and positioned control points. Thanks to the effect of the sealing material and the control of the double-plug grouting core pipe, operations such as fixed-point, quantitative, intermittent, or repeated grouting can be realized.

(2) Strong operability: The grout stop system adopts a double-plug grout stop system for bidirectional sealing (upper and lower). One set of plugs includes a ring of grouting holes, which reduces the possibility of grout overflow and leakage. The grout stop system can move up and down in the pipe, enabling repeated grouting in a specific area or easy switching of grouting sections to achieve segmented grouting. In addition, according to the geological characteristics of different soil layers, it is convenient to change the grout with different mix ratios and adjust the grouting pressure.

(3) Economic and environmental protection: The grouting work platform occupies a small area, saving land use. By controlling the appropriate grouting pressure, targeted treatment of a specific area can be achieved, reducing the consumption of cement grout. At the same time, the sleeve valve pipe can be reused, which fully saves the construction cost while achieving the expected treatment effect.

5. Construction technology of the sleeve valve pipe grouting method

The construction process of sleeve valve pipe grouting generally consists of the following steps: leveling the construction site → delivering materials and equipment to the site → setting out and positioning → drilling → installing and embedding sleeve valve pipes → injecting casing material → grouting into karst caves → quality inspection.

5.1. Drilling

Boundary exploration holes shall be drilled. For small karst caves with a maximum projected side length of less than 5 m (revealed by geophysical exploration), boundary exploration holes may be omitted, and grouting holes can be drilled directly. For karst caves with a maximum side length of more than 5 m, a circle of boundary exploration holes shall be set along the contour line of the karst cave. If a karst cave is detected, drilling shall be conducted 2 m outward from the detected position until no karst cave is found, so as to determine the actual contour line of the karst cave. In this project, for the treatment of karst caves under pile foundations, grouting holes shall first be drilled 1 m around the pile foundations according to the detection results. Other grouting holes shall be arranged in a quincunx pattern with a hole spacing of 2 m × 2 m. Different drilling tools shall be used according to different geological conditions. The layout of grouting holes for a single pile foundation is shown in **Figure 1**. With the pile foundation as the center, four grouting holes shall be arranged at a spacing of 1 m in the first layer, and the second and third layers shall be arranged in a quincunx pattern at a spacing of 2 m. The layout of grouting holes for a single bearing platform is shown in **Figure 2**. It is superimposed based on the layout principle of grouting holes for a single pile foundation. The first layer shall be arranged at a spacing of 1m, and the second and third layers shall be arranged in a quincunx pattern at a spacing of 2 m.

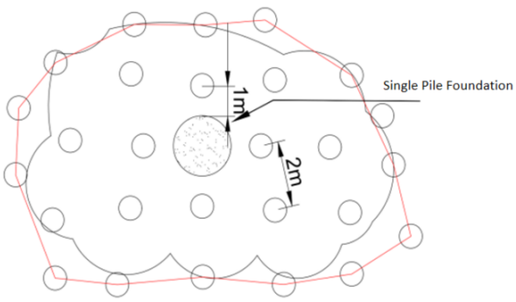


Figure 1. Schematic diagram of grouting for a single pile foundation

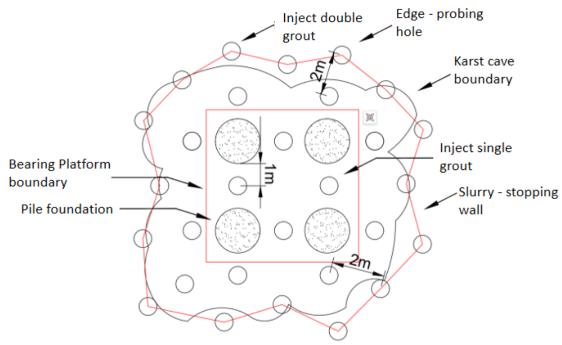


Figure 2. Schematic diagram of grouting for a single bearing platform

5.2. Lowering of sleeve valve pipes

Both solid pipes and perforated pipes are used as grouting pipes. According to the core drilling survey results, solid pipes are used for grouting above the top plate of the karst cave, while perforated pipes are used for grouting in the cavity of the karst cave. To ensure the grouting effect, a bottom plug must be installed at the bottom of the grouting pipe; after the installation of the grouting pipe is completed, a rubber cover shall be added at the pipe orifice for protection. The orifice of the grouting pipe shall be 10–20 cm above the ground, and the pipe shall be lowered to a position 30–50 cm below the bottom of the karst cave. After the lowering of the grouting pipe is finished, fill the pipe with clean water to check its airtightness.

5.3. Injection of casing material

To prevent grout backflow during the grouting process, casing material must be filled between the wall of the sleeve valve pipe and the soil layer, and the filling depth shall reach the bottom of the sleeve valve pipe. Grouting for the grout stop section shall be carried out 1–2 m away from the hole orifice to avoid grout overflow during grouting. During the initial grouting, the liquid level may drop, so it is necessary to inject the grout stop material repeatedly. After the injection of the casing material is completed, the grouting operation can only be carried out after waiting for at least 24 hours to allow the material to reach the required strength. The mix ratio of the casing material (by mass) is bentonite:cement:water = 2:1:9, and the mix ratio of the grout stop material (by mass) is water:cement = 1:1 [4].

5.4. Grouting

After the casing material reaches the required strength, a water injection test shall be conducted: clean water is injected into the grouting pipe and pressurized to achieve loop opening, with the loop opening pressure adopted in this project being 0.3 MPa to 0.5 MPa. A successful loop opening is indicated by a sudden drop in pressure accompanied by a sharp increase in water injection volume during the pressurization process, during which the grout absorption capacity of the stratum and the smoothness of the grouting pipe shall also be evaluated. For the holes around the karst cave in this project, double grouting is adopted, with the water-cement ratio of the cement grout being 1:1 (cement:water), the Baume degree of water glass being 30–40 Be, and the volume ratio of cement grout to water glass being 1:(0.5–0.8); the mix ratio must be determined through on-site proportioning tests to control the setting time of the double grout within 45–60 seconds, with the pressure set at 0.3–0.8 MPa, 3–4 grouting cycles, and an interval of 6–10 hours between each cycle. The central area of the karst cave is filled with single grout, with a water-cement ratio of (1–1.4):1 (water:cement), a grouting pressure of 0.5–1.0 MPa, three grouting cycles, and an interval of 6–10 hours between each cycle [5].

The grouting process shall follow the sequence of "treating large caves first and small ones later, and grouting from the outside to the inside." The grouting equipment and process are shown in **Figure 3**. Segmentally retreating grouting from bottom to top is performed using the front-section perforated pipe. The grouting length per segment is controlled at approximately 0.3–0.5 m, and the retreating section shall be removed promptly when the retreat length exceeds one section. The grouting speed at the top and bottom of the karst cave is controlled at 20–50 L/min, and 30–70 L/min for other parts. The final grouting pressure for peripheral holes is 0.6–0.8 MPa, and 0.8–1.0 MPa for central holes. Grouting can be stopped when the pressure is stabilized for no less than 10 minutes, and the grouting speed should not exceed 1/4 of the initial grouting speed.

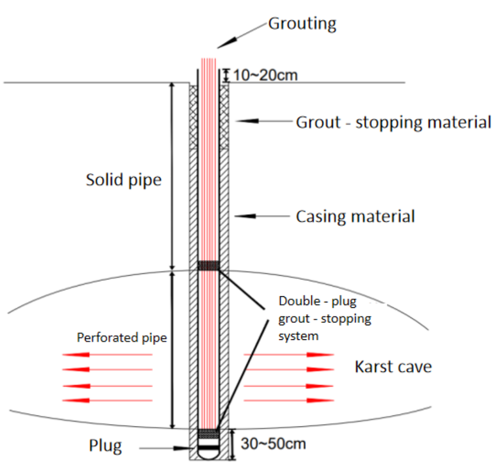


Figure 3. Schematic diagram of sleeve valve pipe grouting

6. Precautions during construction

When dealing with large-volume karst caves or highly connected bead-shaped karst caves where grouting is difficult to complete, measures can be taken appropriately, such as increasing the concentration of cement grout, adopting intermittent grouting, adding accelerators, or switching to double-grout grouting. If necessary, materialfeeding holes can be drilled to fill the caves with C15 plain concrete or M10 cement mortar [6,7].

Grouting shall be carried out continuously. If grouting needs to be interrupted due to special circumstances, it shall be resumed in a timely manner; otherwise, the sleeve valve pipes shall be cleaned immediately to ensure unobstructed flow inside. When resuming grouting, if the grouting speed is close to that before the interruption, the original grout mix ratio shall be used to continue grouting; if the grouting speed is significantly lower than that before the interruption, the concentration of the grout shall be increased step by step [8].

During grouting, if the returned grout becomes thicker, fresh grout with the same mix ratio shall be replaced promptly to continue pouring [9]. If grout leakage or overflow occurs, joint sealing treatment shall be conducted immediately. Comprehensive measures shall be adopted, such as plugging with double grout, appropriately reducing the grouting speed and pressure, adjusting the grout concentration, and extending the grouting interval [10].

7. Conclusion

To summarize, the pre-treatment of small-to-medium-sized karst caves (with a height of 4–10 m) and bead-shaped karst caves at pile foundation construction sites using sleeve valve pipe grouting with double grout can effectively prevent safety risks such as hole collapse and ground subsidence during construction. Meanwhile, it significantly improves the quality of hole formation. This technology can provide technical experience for pile foundation construction in similar areas with strongly developed karst in Shenzhen. The promotion of this technology will bring substantial benefits in terms of construction progress, quality, and safety, and thus holds certain guiding significance.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Yang L, Zhou Y, Huang Y, et al., 2024, Field Tests on Sleeve Valve Pipe Applied to Post-Grouting of Cast-in-Place Piles. Sichuan Building Materials, 50(05): 68–69 + 78.

[2] Chen X, Feng X, Wang X, et al., 2024, Mix Ratio Optimization of Casing Material for Sleeve Valve Pipe Grouting. Journal of Luoyang Institute of Science and Technology (Natural Science Edition), 34(01): 39–43.

[3] Han J, An S, 2019, Application Analysis of Sleeve Valve Pipe Grouting in Subgrade Karst Cave Treatment. Green Building Materials, (02): 143 + 145.

[4] Gong S, 2021, Application of Membrane Bag Sleeve Valve Pipe Grouting Technology in Karst Subgrade Treatment. Jushe, (16): 89–90.

[5] Cambefort H, 1977, The Principles and Applications of Grouting. Quarterly Journal of Engineering Geology, 10(2): 57–95.

[6] Industry Standard of the People's Republic of China, 2010, JGJ/T 211-2010 Technical Specification for Cement-Sodium Silicate Double-Grout in Construction Engineering, China Architecture & Building Press, Beijing.

[7] National Standard of the People's Republic of China, 2011, GB 50007-2011 Code for Design of Building Foundation, China Planning Press, Beijing.

[8] Shenzhen Municipal Engineering Construction Standard, 2017, SJG 41-2017 Code for Geotechnical Investigation

and Foundation Design of Shenzhen, Shenzhen Municipal Housing and Construction Bureau, Shenzhen.
[9] Cheng X, Zhang F, 1998, Civil Engineering Grouting Construction and Effect Testing, Tongji University Press, Shanghai.
[10] Wu X, Hu Y, Li L, et al., 2012, Grouting Technology and Management, China University of Geosciences Press, Wuhan.

Integrated Services Platform of International Scientific Cooperation

Innoscience Research (Malaysia), which is global market oriented, was founded in 2016.Innoscience Research focuses on services based on scientific research. By cooperating with universities and scientific institutes all over the world, it performs medical researches to benefit human beings and promotes the interdisciplinary and international exchanges among researchers.

Innoscience Research covers biology, chemistry, physics and many other disciplines. It mainly focuses on the improvement of human health. It aims to promote the cooperation, exploration and exchange among researchers from different countries. By establishing platforms, Innoscience integrates the demands from different fields to realize the combination of clinical research and basic research and to accelerate and deepen the international scientific cooperation.

Cooperation Mode

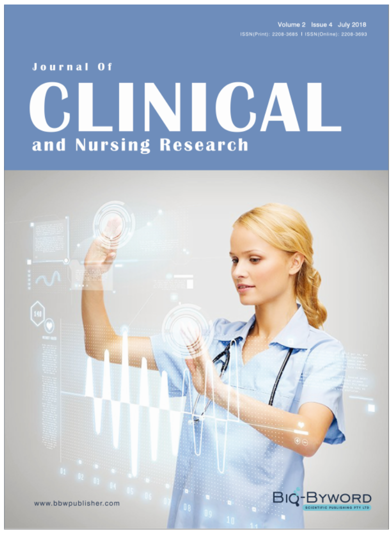
Our Journals

The *Journal of Architectural Research and Development* is an international peer-reviewed and open access journal which is devoted to establish a bridge between theory and practice in the fields of architectural and design research, urban planning and built environment research.

Topics covered but not limited to:

- Architectural design
- Architectural technology, including new technologies and energy saving technologies
- Architectural practice
- Urban planning
- Impacts of architecture on environment

Journal of Clinical and Nursing Research (JCNR) is an international, peer reviewed and open access journal that seeks to promote the development and exchange of knowledge which is directly relevant to all clinical and nursing research and practice. Articles which explore the meaning, prevention, treatment, outcome and impact of a high standard clinical and nursing practice and discipline are encouraged to be submitted as original article, review, case report, short communication and letters.



Topics covered by not limited to:

- Development of clinical and nursing research, evaluation, evidence-based practice and scientific enquiry
- Patients and family experiences of health care
- Clinical and nursing research to enhance patient safety and reduce harm to patients
- Ethics
- Clinical and Nursing history
- Medicine

Journal of Electronic Research and Application is an international, peer-reviewed and open access journal which publishes original articles, reviews, short communications, case studies and letters in the field of electronic research and application.

Topics covered but not limited to:

- Automation
- Circuit Analysis and Application
- Electric and Electronic Measurement Systems
- Electrical Engineering
- Electronic Materials
- Electronics and Communications Engineering
- Power Systems and Power Electronics
- Signal Processing
- Telecommunications Engineering
- Wireless and Mobile Communication