WEP Warwick Evans Publishing

Academic Journal of Management Science and Engineering

ISSN: 3080-9827 (Print), ISSN: 3080-9835 (Online) | Volume 1, Number 2, Year 2026
DOI: https://doi.org/10.62051/ajmse.v1n2.20
Journal homepage: https://ajomse.com



Prefabricated Wall Panels: A Review of Structural Systems, Mechanical Properties, and Evaluation Indices

Zhanhang Cheng

School of Pipelinel Engineering College, Xi'an Shiyou University, Xi'an, Shaanxi, 710065 China

ABSTRACT

With the rapid acceleration of prefabricated construction worldwide, new architectural wall panels have emerged as a critical vanguard of sustainable, high-efficiency engineering. Serving as a new generation of cement-based composites and lightweight structural assemblies, modern prefabricated panels feature ultra-high strength, exceptional toughness, superb thermal or acoustic insulation, and outstanding durability. This paper provides a comprehensive, deep-dive academic review synthesizing recent advancements across ultra-high space embedded wall panels, autoclaved lightweight aerated concrete (ALC) panels, light steel keel wallboards, and layered concrete-insulated composite systems. By aggregating recent empirical and numerical datasets, this review systematically dissects material composition optimization, joint connection mechanisms (rigid vs. flexible), structural reinforcement parameters, and multi-criteria lifecycle evaluation index systems. The findings demonstrate that while prefabricated wall technologies are maturing rapidly, critical challenges remain regarding the optimization of structural composite action, the elimination of localized thermal bridges, and the harmonization of objective-subjective lifecycle weighting. This review highlights prospective research paradigms to guide multi-scale testing, numerical standardization, and intelligent construction in green infrastructure.

KEYWORDS

Prefabricated Buildings; Composite Wall Panels; Mechanical Properties; Connection Nodes; Multi-criteria Lifecycle Evaluation.

1. INTRODUCTION

Traditional civil engineering paradigms have historically relied heavily on cast-in-place reinforced concrete structures and heavy masonry division walls [1]. While these conventional systems offer familiar construction pathways and high initial structural mass, they impose severe penalties on modern urban development [1, 2]. Traditional wet construction trades are notoriously characterized by prolonged on-site execution cycles, intensive labor dependency, vast material wastage, and substantial carbon footprints [1, 3]. Furthermore, traditional heavy claddings generate significant structural self-weight, which exponentially amplifies the seismic mass of buildings and demands oversized, expensive foundation designs [1, 4].

In response to global mandates for carbon neutrality, resource conservation, and industrialization, the architectural sector is undergoing a profound structural transition toward prefabricated and modular systems [3]. Within this industrial shift, non-structural and semi-structural building envelopes—specifically new-generation prefabricated wall panels—have emerged as a core focus of technological innovation [2, 4]. By migrating core fabrication workflows from uncontrolled field environments into automated, high-precision industrial facilities, prefabrication guarantees superior material

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consistency, drastically curtails on-site assembly timelines, and minimizes localized environmental pollution [1, 3].

1.1. Material and Structural Evolution of Building Envelopes

Modern architectural frameworks demand that building envelopes fulfill multiple functional requirements [4]. Contemporary wall configurations are no longer viewed merely as passive spatial dividers; instead, they are engineered to serve as multi-tiered, high-performance protective barriers [1, 4]. These systems must simultaneously optimize structural integrity (such as resisting high out-of-plane wind pressures and seismic drift), environmental shielding (thermal insulation and energy conservation), building physics (acoustic isolation and moisture control), and severe multi-hazard resilience (fire containment and blast mitigation) [1, 2, 4].

To satisfy these diverse performance thresholds, prefabricated wall panels have evolved away from single-layer, homogeneous materials toward advanced multi-layered composite architectures and optimized skeletal assemblies [1, 4]. Layered sandwich wall boards systematically separate individual engineering demands: high-density, fiber-reinforced cementitious composites are deployed at the exterior faces to withstand impact and tension, while ultra-low-density polymer or mineral cores are encapsulated within the interior to arrest thermal transmission [4]. Concurrently, lightweight cold-formed thin-walled steel keel assemblies leverage high strength-to-weight ratios to construct ultra-light framing systems suitable for rapid industrial and residential scale-up [1].

1.2. Key Vulnerabilities and Current Technical Bottlenecks

Despite documented engineering benefits, the structural integration of prefabricated panels into large-scale building frameworks introduces complex technical challenges [2, 5]. When prefabricated enclosures are coupled with flexible primary structures, such as steel or reinforced concrete frames, the joint interfaces become zones of severe stress concentration [2, 5]. Under cyclic lateral loads induced by wind forces or seismic events, traditional rigid connection nodes heavily restrict inter-story drift [2]. This lack of deformation capacity frequently results in localized corner crushing, premature panel buckling, and catastrophic joint separation before the primary frame can fully mobilize its energy dissipation mechanisms [2].

This vulnerability is magnified in ultra-high space designs—such as modern airport terminals, logistics hubs, and grand exhibition complexes—where individual floor clearances often exceed 6 m [2]. Because transport logistics limit the maximum dimensions of single precast elements, ultra-high spatial applications necessitate complex modular splicing [2]. These connection seams are highly susceptible to out-of-plane flexural failure and localized cracking [2]. Additionally, the mechanical connectors penetrating insulation layers to maintain sandwich integrity generate severe localized thermal bridges, causing significant heat leakage and compromising the building's net thermal efficiency [4]. Finally, the proliferation of diverse material options and splicing node typologies has complicated component selection, highlighting a critical need for rigorous multi-criteria lifecycle evaluation indices to guide sustainable engineering decisions [3].

1.3. Scope and Objectives of This Review

To address these challenges and establish a unified reference for future research, this paper presents a comprehensive review synthesizing the state-of-the-art in prefabricated wall panel technologies. Drawing upon recent empirical, numerical, and field data, this review is structured into four core technical sections: a rigorous taxonomy of modern wall panel typologies [1, 4]; an in-depth analysis of interface kinetics and horizontal splicing configurations [2, 5]; a critical evaluation of physical and mechanical performance metrics [1, 4]; and a methodological breakdown of multi-criteria lifecycle evaluation frameworks [3]. By synthesizing current technical bottlenecks, this review outlines

prospective multi-scale testing and numerical standardization paradigms required to advance intelligent, zero-carbon building facades.

2. CLASSIFICATION AND STRUCTURAL COMPOSITION OF MODERN WALL PANELS

2.1. Cementitious and Advanced Concrete Facings

The facing layer of a composite wall panel represents the primary defense against out-of-plane wind loads, accidental impacts, and environmental degradation [4]. Traditional normal-strength concrete faces introduce high dead weights and low tensile capacities, leading to early cracking [4]. Consequently, research has shifted heavily toward high-performance, fiber-reinforced, and ultra-dense cementitious matrices [4, 6]. The mechanical properties and reinforcement mechanisms of predominant cementitious facings are categorized below:

Foam Concrete (FC): Utilizing internal air voids to promote thermal and acoustic damping, reinforced foam concrete typically exhibits a compressive strength of 25 MPa and a tensile strength of 1.9 MPa [4]. Its ultra-lightweight properties make it highly pumpable and cost-effective when combined with steel mesh or protective shells [4].

Ultra-High Performance Concrete (UHPC): Representing a premier generation of cement-based composites, steel fiber-reinforced UHPC can reach an extraordinary compressive strength exceeding 150 MPa [6]. The microstructural density of UHPC is achieved via stringent raw material constituent optimization, including the elimination of coarse aggregates, the use of high-quality Portland cement (high C_3S content), and the integration of highly reactive silica fume (average size 0.1μm) [6]. The secondary pozzolanic reaction forms additional highly stable C-S-H gel, making UHPC an ideal facing material for extreme environments [6].

2.2. Core Insulation Layer Configurations

The internal core sandwiched between concrete facings defines the panel's thermal barrier and fire-containment capability. The structural properties of the three dominant core typologies vary considerably:

Expanded Polystyrene (EPS) Foam: Featuring an ultra-low density comprised of discrete gaseous pores enclosed in a polymer matrix, EPS offers low material costs and ease of prefabrication [5]. However, its widespread structural implementation is bounded by high flammability and rapid thermal degradation [5].

Rock Wool: Manufactured from basalt and dolomite, rock wool is an ideal A-class non-combustible material [5]. It offers outstanding fire mitigation and acoustic absorption, though its thermal resistance severely degrades if water vapor condenses within its fibrous matrix [5].

Polyurethane (PU) Foam: Boasting superior thermal resistance, PU foam is often infused into spatial grid lattices to construct highly rigid, lightweight sandwich assemblies [5].

2.3. Integrated Wall Typologies and Assemblies

Based on different structural architectures, prefabricated walls are categorized into several core typologies:

Autoclaved Lightweight Aerated Concrete (ALC) Panels: Exhibiting an optimal balance of lightweight design, structural processability, excellent thermal insulation, and fire protection, ALC panels represent a highly adaptively viable configuration for general building frameworks [1, 2].

Light Steel Keel Composite Walls: Comprised of cold-formed thin-walled steel skeletal components sheathed in facing boards, this assembly reduces total structural self-weight by more than 50% compared to traditional masonry or concrete frames [4]. It exhibits superb seismic flexibility, though it requires complex assembly installation [4, 12].

3. CONNECTION MECHANISMS, SPLICING, AND JOINT INTERFACES

3.1. Rigid vs. Flexible Joint Interfaces

The boundary nodes connecting prefabricated panels to primary structural steel or concrete frames govern the stress transfer and overall safety of the structure **[1, 2]**.

Rigid Connections: Typical nodes rely on dense U-shaped clips, rigid tube clamps, or welded anchor plates [2]. While rigid configurations significantly enhance initial lateral stiffness, they heavily restrict inter-story drift [1, 14]. Under cyclic loading, this restriction triggers severe localized squeezing, corner crushing, and rapid crack propagation from the panel boundaries [1].

Flexible Connections: Designed to isolate the panel from the primary frame's deformation, flexible connections allow controlled sliding or rotation [1]. Advanced nodes, such as Damage-Control Precast Walls (DCPW) and Cantilever Bracket-Ring (CHG) connectors, utilize specialized oval limit bolt holes to decouple the wall from destructive frame deformation, ensuring excellent cooperative kinematics and reducing wall damage [1, 9].

3.2. Splicing Methodologies under Ultra-High Space Constraints

Ultra-high space designs refer to structural layouts where individual story heights exceed 6 m, strictly demanding modular panel splicing [1]. Two primary horizontal splicing schemes are utilized:

Staggered Splicing: This configuration arranges vertical joints in a staggered pattern. Out-of-plane bending experiments indicate that the flexural capacity increases monotonically with the staggered distance, with a minimum horizontal staggered length of 900 mm strictly recommended [1, 11].

Vertical Splicing: The "short bottom panel + full top panel" technique shifts the seam joint away from peak moment zones, simplifying hoisting logistics and enhancing wind pressure resistance [1].

3.3. Shear Connectors and Thermal Efficiency Optimization

In insulated concrete sandwich structures, traditional connectors utilizing dense concrete blocks or bent carbon steel ties generate severe thermal bridging [5]. To optimize energy efficiency, advanced structures utilize fiber-reinforced polymer (FRP) ties, such as GFRP and CFRP [5, 8]. These connectors minimize heat transfer across the insulation core (due to their extremely low thermal conductivity of approximately 1.0 to 5.0 W/(m·K)) while ensuring reliable long-term load transfer [5].

4. MECHANICAL AND PHYSICAL PERFORMANCE CHARACTERIZATION

4.1. Flexural, Compressive, and Shear Static Kinetics

The static structural performance of prefabricated wall systems depends heavily on component geometry and supplemental stabilizing measures [4, 5]. For light steel keel configurations, the shear span ratio (λ) governs the failure mechanics: under a low span ratio (λ=0.5-1.1), components undergo pure shear failure, whereas moderate ratios trigger coupled flexural-shear buckling modes [4]. In ultra-high configurations, installing additional horizontal steel beams coupled with heavy hanging

columns (e.g., spaced every 4.8 m) successfully decreases the unsupported panel envelope dimension, preventing geometric bending [1].

4.2. Seismic Resilience and Hysteretic Damping

Low-cycle cyclic lateral loading tests reveal distinct energy dissipation characteristics [4, 10]. Incorporating internal diagonal bracing steel strips inside light steel frames significantly elevates lateral shear capacity and hysteretic energy dissipation [4]. High-axial compression cyclic testing demonstrates that precast concrete sandwich shear walls retain highly stable, full hysteretic loops and excellent ductility under severe axial loads, making them suitable for seismic high-rise construction [5].

4.3. Building Physics: Thermal, Fire, and Acoustic Performance

Thermal and Fire Performance: Fire endurance tests indicate that polyisocyanurate (PIR) core sandwich walls coated with thick gypsum plaster boards exhibit superior thermal shielding [5]. However, polyurethane-based cores may generate vast volumes of hazardous carbon monoxide gas under high heat, presenting severe fire safety risks [5].

Acoustic Insulation: Noise mitigation is achieved via multi-layered porous cores or advanced Sandwich Structures Compounded with Resonant Acoustic Metamaterials (SSCRAM) [5]. By modeling internal energy fields as a spring-mass configuration, SSCRAM panels capture and attenuate low-frequency acoustic energy effectively [5].

5. MULTI-CRITERIA AND LIFE-CYCLE EVALUATION INDEX SYSTEMS

5.1. Indicator Classification and Structural Matrix Dimensions

As the material compositions of prefabricated panels diversify, establishing a scientific evaluation model becomes mandatory [3]. Contemporary frameworks divide these models into "Multi-Angle Comprehensive Evaluation Index Systems" and "Whole Life-Cycle Comprehensive Evaluation Index Systems" [3]. A comprehensive life-cycle model tracks the wall panel across five phases (design, production, construction, use, and recycling) and groups parameters into three core dimensions: Technical Performance (mechanical and physical coefficients), Economic Performance (cost and payback period), and Environmental Performance (energy consumption and carbon emissions) **[3]**.

5.2. Mathematical Optimization Methodologies

Advanced frameworks combine subjective and objective mathematical weighting models [3]. The Analytic Hierarchy Process (AHP) is typically implemented to determine subjective weights via expert pairwise comparison matrices [3, 13]. The Criteria Importance Through Intercriteria Correlation (CRITIC) method computes objective weights based on empirical operational data [3]. Once weights are established, they are processed through decision-making scoring algorithms like TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) or Grey Relation Analysis (GRA) to scientifically rank wall panel alternatives [3].

6. FUTURE PROSPECTS

Although significant progress has been made in the theoretical research and engineering applications of modern wall panels, widespread adoption still faces challenges such as incomplete design standards and complex composite behavior modeling. To further promote the development of sustainable building envelopes, future research should focus on the following paradigms:

6.1. Multi-Hazard Validation under Extreme Environments

Current research predominantly focuses on static flexural capacity and standard cyclic lateral loading [1]. There is a profound need for multi-scale experimental validation under coupled extreme hazards (e.g., simultaneous wind-seismic actions or fire-after-earthquake scenarios). For ultra-high spatial applications, the long-term structural degradation of splicing joints under severe environmental exposures requires extensive chamber testing to ensure lifecycle reliability [2].

6.2. Optimization of Composite Action and Advanced Connectors

The theoretical quantification of partial mechanical composite action between the inner and outer concrete layers across soft insulation cores remains contentious [4]. Future research must prioritize the development of ultra-low thermal conductivity, ultra-high-stiffness fiber-reinforced polymer (FRP) connectors, combined with unified mathematical models to accurately predict the nonlinear partial composite behavior of sandwich walls [4].

6.3. Digital Twins and Intelligent Construction

The performance assessment of prefabricated panels currently relies heavily on static, discrete decision-making frameworks [3]. Future paradigms should deeply integrate multi-criteria lifecycle evaluation indices into commercial finite element platforms and Building Information Modeling (BIM) [3]. Developing "Digital Twins" for architectural facades—coupled with embedded sensors—will enable the real-time tracking of joint displacements and automated lifecycle maintenance management [2, 3].

6.4. Standardization of Design Codes and Guidelines

The rapid material innovation and joint complexity of composite wall panels have significantly outpaced the development of unified regulatory standards [1, 5]. Formulating comprehensive, universally accepted engineering design codes—particularly concerning maximum modular splicing dimensions in ultra-high spaces, the ultimate deformation limits of sliding nodes, and standardized fire-toxicity thresholds for organic cores—is imperative. Establishing these codes will standardize engineering practices, mitigate construction risks, and accelerate the global commercialization of sustainable prefabricated infrastructure [2, 4].

7. SUMMARY

(1) Prefabricated wall panel preparation and application technology is becoming mature, forming a relatively complete technical system. By optimizing raw material selection, structural design, and construction processing, composite wall panels with stable, superior performance can be consistently produced. In material composition optimization, a design theory centered on lightweight insulation cores and high-strength facings has been established; in structural processing, complete installation procedures including staggered splicing and flexible connections have been developed to adapt to ultra-high spaces; in quality control, comprehensive full-process evaluation systems tracking technical, economic, and environmental impacts from raw materials to finished products have been instituted.

(2) The mechanisms underpinning prefabricated wall panels' superior structural and physical performance have been deeply elucidated. Structural and microstructural analyses indicate that their outstanding multi-hazard resistance mainly arises from their layered sandwich configurations, optimized joint interfaces, and energy-dissipating skeletal frames. Joint mechanism studies further reveal that transitioning from traditional rigid anchors to flexible connectors significantly delays

crack propagation, minimizes localized thermal bridging, and remarkably enhances the cooperative deformation capacity between the precast panels and the primary building frames.

ACKNOWLEDGMENTS

Supported by the National Natural Science Foundation of China (Grant No. 52308204); the Natural Science Basic Research Program of Shaanxi Province (Grant No. 2022JQ-301); and the Natural Science Foundation of Shandong Province (Grant No. ZR2024ME094).

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