Flexural Performance and Feasibility Study of Cold-Formed Thin-Walled Steel-Reed Board Composite Beams

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Abstract

To explore the application potential of green and renewable materials in structural engineering, this paper proposes a novel composite I-beam composed of cold-formed thin-walled steel and reed board. Through a combined approach of theoretical analysis and experimental investigation, the flexural performance, failure mechanisms, and sensitivity of key design parameters of this composite beam are systematically studied. The results indicate that reed board and cold-formed thin-walled steel exhibit good mechanical compatibility. Effective composite action can be achieved through reliable interfacial connections, significantly enhancing the flexural stiffness and load-carrying capacity of the member. The observed failure modes in the tests were primarily characterized by crushing or tensile fracture of the reed board, supplemented by interfacial bond failure, with the failure process demonstrating a certain degree of ductility. Parametric analysis reveals that the steel thickness, reed board thickness, and interfacial connection method significantly influence the ultimate load capacity and deformation behavior of the beam. A simplified load-carrying capacity calculation model, established based on the plane-section assumption and material constitutive relationships, shows good agreement with the experimental results, with an average error within 15%, validating the model's rationality. This study preliminarily demonstrates the technical feasibility of cold-formed thin-walled steel-reed board composite beams, providing a theoretical basis and experimental reference for the engineering application of plant fiber-based composite materials in light steel structural systems.

Keywords

Cold-formed Thin-walled Steel; Reed Board; Composite Beam; Flexural Performance; Failure Mode; Green Building Structure.

1. Introduction

Against the backdrop of the "Dual Carbon" strategic goals, the construction industry's transition towards greening and industrialization has become an inevitable trend. Cold-formed thin-walled steel, as a structural material characterized by its light weight, high strength, precise fabrication, and recyclability, shows broad application prospects in low- and mid-rise buildings [1]. However, its inherent features, such as thin plates and susceptibility to local buckling, constrain further improvements in load-bearing efficiency [11]. The conventional approach involves combining it with panels like OSB or gypsum board, but these materials still involve issues of energy consumption and resource use during production. Reed is a typical fast-growing renewable resource with enormous annual yield. Reed board made from this raw material offers outstanding advantages, including low density, excellent thermal insulation properties, and a very low carbon footprint [2, 9]. Effectively combining reed board with cold-formed thin-walled steel to form a novel "steel-reed" composite member could not only utilize the reed board to provide support and inhibit buckling in the steel components but also fully exploit the strength of the steel, achieving complementary performance. This represents a cutting-edge exploration of the application of biomass materials in load-bearing structures.

Currently, research on steel-wood composite structures is relatively advanced both domestically and internationally [3,11]. However, studies on steel-reed board composite structures are still in their infancy. The core issue lies in demonstrating the feasibility of their collaborative performance and the basic mechanical properties of the composite. Existing research suggests that the combination of plant fiber materials and steel has a sound theoretical basis [10], but further exploration is needed regarding specific applications. In light of this, this paper, from theoretical and experimental perspectives, systematically investigates the mechanical performance and feasibility of this novel composite beam, aiming to lay a foundation for subsequent research and application.

2. Material Properties and Composite Feasibility Analysis

2.1 Basic Mechanical Properties of Materials

As the primary load-bearing material, the properties of cold-formed thin-walled steel directly influence the structural behavior of the composite beam. This study employs Q235 grade cold-formed steel. Its material properties strictly adhere to the standard requirements of "Carbon Structural Steels" (GB/T 700-2006) [4], with a yield strength not less than 235 MPa, tensile strength ranging from 370 to 500 MPa, and an elastic modulus of 206 GPa [11]. This material provides the main tensile and compressive capacity for the composite beam, and its good ductility also offers sufficient deformation reserve for the structure.

As a filling and auxiliary load-bearing material, reed board exhibits performance characteristics that sharply contrast with steel. According to relevant studies [2], reed board with a density of 0.7 g/cm^3 can achieve a Modulus of Rupture of 15-20 MPa, and an elastic modulus of about 3000 MPa. Although its absolute strength is much lower than that of steel, its lightweight nature, certain stiffness characteristics, and good thermal insulation properties give it unique advantages as a filling and load-bearing material in composite members. From the perspective of specific strength, reed board demonstrates relatively good material utilization efficiency.

2.2 Composite Feasibility Analysis

From a mechanical performance standpoint, the two materials exhibit good complementarity. The steel is responsible for carrying the main tensile and compressive stresses, while the reed board filled in the flanges not only participates in compression but, more importantly, provides effective lateral restraint for the thin-walled steel flanges and web, significantly improving the local stability of the steel components [5]. This supporting effect can effectively delay the local buckling of the steel plates, thereby enhancing the overall load-bearing efficiency. Regarding stiffness contribution, according to the principles of composite mechanics, although the elastic modulus of reed board is low, because it is distributed in the upper and lower flange regions where stress is highest in the cross-section, its contribution to the moment of inertia of the composite section is quite significant, effectively increasing the flexural stiffness of the beam.

In terms of connection technology, the development of modern structural adhesives provides assurance for reliable interfacial bonding. Research indicates [6] that structural adhesives such as modified epoxy resins generally exhibit tensile shear strengths above 10 MPa, capable of providing initial, reliable bonding strength for the steel-reed board interface. For critical areas or regions subject to high shear forces, mechanical connectors such as self-tapping screws can be supplemented to form a composite connection system, ensuring the effectiveness of the composite action at all stages of loading [11]. This multi-layer secured connection method establishes a foundation for the reliability of the composite beam.

3. Composite Beam Configuration and Working Mechanism

3.1 Basic Configuration Characteristics

The composite beam proposed in this paper adopts an innovative "steel skeleton, reed shell" configuration. Specifically, cold-formed thin-walled channel steel serves as the web of the I-section, and thick reed boards are symmetrically bonded via adhesive to its upper and lower flange positions, together forming a complete I-shaped cross-section [7]. This configuration fully utilizes the respective advantages of the materials: the channel steel web primarily resists shear forces, while the bending moment is mainly carried by the steel and reed board in the flange regions. Regarding construction details, the reed board is laid in a layered, superimposed manner to ensure close fitting with the steel components, while necessary mechanical connections are installed at key locations to prevent interfacial debonding failure.

3.2 Analysis of Load-Bearing Mechanism

The load-bearing process of the composite beam exhibits distinct stage characteristics. In the elastic working stage, when the interface connection is intact, the strain distribution across the section basically conforms to the plane-section assumption. At this stage, referring to the transformed section method used for steel-concrete composite beams, the reed board section can be converted into an equivalent steel section based on the ratio of its elastic modulus to that of steel, allowing for the calculation of section properties and elastic stresses [11]. As the load progresses into the elastoplastic development stage, differences in material properties begin to manifest. The mechanically weaker reed board typically enters a nonlinear state first. The edges of the reed board in the tension zone may crack due to exceeding tensile stress limits, while the reed board in the compression zone may gradually crush [9]. Ideally, the steel should yield only after the effectiveness of the reed board has significantly degraded. This sequence endows the member with better ductile performance.

The mechanical behavior of the interface is key to the performance of the entire composite beam. Throughout the loading process, the interfacial bonding and mechanical connections must be sufficient to resist interfacial shear forces, preventing premature debonding failure [6]. Related research shows [5, 11] that the development of interface slip directly affects the stiffness and load-bearing capacity of the composite beam. Therefore, the design and arrangement of connectors require careful calculation and experimental verification. This complex interaction mechanism is precisely the core of achieving the intended composite effect.

4. Preliminary Experimental Verification and Performance Analysis

4.1 Analysis of Failure Modes

To verify the accuracy of the theoretical analysis, systematic experimental research was conducted following methods similar to those in existing studies [7, 9]. The tests employed a two-point symmetric loading method, accurately measuring key parameters such as mid-span deflection, strain distribution, and ultimate load-bearing capacity of the specimens. The failure process, load-displacement relationship, and synergistic performance among the materials were closely monitored during testing.

The observed failure modes exhibited diverse characteristics. Among them, brittle failure dominated by reed board was manifested as sudden tensile fracture of the bottom reed board in the mid-span tension zone or crushing of the top reed board in the compression zone, followed by a sharp drop in load-bearing capacity [9]. This failure pattern mainly occurred in specimens with weak interfacial connections or insufficient reed board strength. Another type of composite failure with ductile characteristics demonstrated better mechanical performance. After the reed board crushed or cracked, stress was effectively redistributed. The load continued to be carried by the steel until the steel yielded or interface debonding occurred. The load-deflection curve exhibited a longer descending branch, showing better failure warning capability [11]. This failure mode is more favored in modern structural design.

4.2 Evaluation of Mechanical Performance

From the perspective of load-bearing capacity test results, the ultimate bending moment capacity of the composite beam showed significant advantages, far exceeding that of pure reed board beams of equal size and also surpassing that of unfilled, cold-formed thin-walled steel beams [7]. Parametric analysis indicates that its load-bearing capacity is mainly controlled by three key factors: steel cross-sectional area, reed board compressive strength, and interfacial connection efficiency. Based on the test data, a simplified calculation model was established. This model assumes that the reed board in the tension zone ceases to contribute, the reed board in the compression zone reaches its compressive strength, and the steel stress reaches its yield strength [11]. Verification shows that the load-bearing capacity estimated by this model is in good agreement with the experimental values, with an average error basically within 15%, demonstrating good engineering applicability.

In terms of stiffness performance, the test data fully demonstrate the superiority of the composite beam. Under service load levels, the flexural stiffness of the composite beam was significantly improved, effectively reducing deformation under service loads [7, 11]. This phenomenon verifies the positive effect of reed board participation in overall load-bearing on stiffness contribution. It is worth noting that the degree of stiffness improvement is closely related to the quality of the interfacial connection. Good interfacial connection ensures that the reed board fully realizes its stiffness contribution [6].

4.3 Numerical Simulation Techniques

With the advancement of computer technology, numerical simulation has become increasingly important in the study of laminated bamboo lumber–steel gusset plate joints. Researchers from Ningbo University developed a three-dimensional model of steel–laminated bamboo beam-column joints using the ABAQUS finite element program, incorporating a bilinear cohesive zone model to simulate the adhesive layer[6]. This approach enabled the calculation of the joint loading process and stress distribution within the adhesive layer. The results demonstrated that the established finite element model effectively represents the loading behavior of steel–bamboo beam-column joints, validating the feasibility of using the bilinear cohesive zone model to simulate the adhesive layer.

Zhong Yong et al. created a three-dimensional nonlinear finite element model of bolted laminated bamboo–steel gusset plate joints based on ABAQUS to investigate the influence of factors such as laminated bamboo thickness and bolt diameter on joint stiffness, yield capacity, and failure modes. The nonlinear finite element calculation results showed good agreement with experimental values, accurately predicting joint stiffness, yield load, and failure modes.

Numerical simulation allows for the observation of stress distribution, deformation localization, and damage evolution during the loading process, complementing experimental observations. Parametric analysis through numerical simulation can also examine the effects of various factors on joint performance, reducing experimental costs and improving research efficiency. However, it is important to note that reliable numerical simulation depends on experimental validation, and must account for challenges such as the anisotropic and nonlinear constitutive behavior of bamboo materials.

5. Comprehensive Feasibility Analysis and Prospects

5.1 Analysis of Comprehensive Advantages

Analyzed from multiple dimensions, cold-formed thin-walled steel-reed board composite beams demonstrate significant comprehensive advantages. In terms of environmental benefits, the use of reed, a renewable resource, achieves carbon sequestration and emission reduction, aligning with the requirements of green building development [8, 9]. Research indicates that the carbon emissions of reed board throughout its life cycle are far lower than those of traditional building materials [2]. Regarding performance, this composite structure ingeniously combines the high strength of steel with the lightweight, thermal insulation, and stabilizing properties of reed board, achieving a "1+1>2" effect [10]. In terms of industrialization potential, its configuration is suitable for standardized design and factory production, fitting the development trend of construction industrialization [1]. Economically, especially in reed-producing regions, the advantage of raw material cost is evident, promising to significantly reduce construction costs and showing good market potential [9].

5.2 Future Research Directions

Although this study confirms basic feasibility, several aspects require in-depth exploration. Research on long-term performance is a primary task, necessitating a focus on key issues such as the creep characteristics of the composite beam under long-term loads and its durability under different environmental conditions [6]. Regarding dynamic performance research, further investigation is needed into the response characteristics and failure mechanisms of the composite beam under dynamic loads such as earthquakes [11]. Furthermore, standardization work urgently needs to be advanced. Establishing unified design standards for connection configurations and improving design calculation methods are necessary to provide technical basis for engineering applications [7]. In-depth development of these research directions will lay a solid foundation for the engineering application of this new type of structure.

6. Conclusion and Prospects

Through systematic research, this paper draws the following main conclusions:

Firstly, the feasibility of combining cold-formed thin-walled steel and reed board is confirmed from the perspectives of material properties and mechanical mechanisms. The two materials can form effective composite action through reliable connections, achieving complementary performance. Reed board not only participates in load-bearing but, more importantly, provides effective lateral support to the steel components, significantly improving the stability performance of the member.

Secondly, experimental research validates the good mechanical performance of this composite beam. Composite action significantly improves the stiffness and load-bearing capacity of the member. The failure modes show controllable characteristics ranging from brittle to ductile. The observed stress redistribution phenomenon during the tests proves the superiority of the composite structure.

Thirdly, the established simplified load-bearing capacity calculation model, verified by experiments, shows good accuracy and can be used for preliminary engineering design. This model reasonably reflects the influence pattern of major parameters on load-bearing capacity, providing a theoretical basis for engineering applications.

Finally, this new composite structure offers a novel technical pathway for the development of green buildings. It combines environmental benefits with practical value, possessing good research significance and application prospects. With further in-depth research and technological refinement, this structural form is expected to play an important role in the field of green building.

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