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Research Progress on Interface Slip Behavior of Steel–Shale Ceramsite Concrete Composite Beams

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ABSTRACT: Steel–shale ceramsite concrete composite beams are promising for green building applications due to their light weight, high strength, and favorable seismic performance. However, interface slip may induce stiffness degradation and increased deflection, compromising structural safety. The underlying slip mechanism remains unclear, and current analytical methods are of limited applicability. This review systematically addresses slip mechanisms, calculation methods, and deformation characteristics. It summarizes the material properties of shale ceramsite concrete and their effect on stud behavior and interfacial slip, evaluates existing slip stiffness models and calculation approaches, and examines methods for predicting slip-induced flexural stiffness reduction and beam deflection. Finally, current research challenges are identified, and future directions are suggested.

KEYWORDS: Shale ceramsite concrete, Composite beam, Slip mechanism, Deflection calculation.

I. INTRODUCTION

The global push for green, low-carbon, and sustainable construction has made structural lightweight design and high performance paramount. Shale ceramsite concrete (SCC), an artificial lightweight aggregate concrete, is an ideal material for this purpose due to its low density, high strength, excellent thermal insulation, and superior seismic resistance [1,2]. Combining SCC with steel in composite beams capitalizes on the strengths of both materials. This synergy significantly reduces structural weight while improving overall stiffness, ductility, and energy dissipation capacity [3,4]. Consequently, steel–SCC composite beams hold great promise for long-span bridges, high-rise buildings, and other structures with stringent seismic requirements, offering considerable practical and economic benefits.

The composite action in these beams is typically provided by shear studs welded to the steel beam and embedded in the concrete flange. However, inherent differences in physical and mechanical properties—such as elastic modulus, Poisson’s ratio, and thermal expansion coefficient—between steel and shale ceramsite concrete, together with deformations in the studs and surrounding concrete under load, induce interfacial slip between the steel beam and concrete slab [5]. This slip reduces composite efficiency, leading to stress redistribution, loss of flexural stiffness, and increased deflection, which compromises both serviceability and ultimate load capacity. Under long-term, cyclic, or seismic loading, progressive slip can accelerate stud damage and concrete cracking, thereby threatening the safety and durability of the structural system [6,7]. A clear understanding of the interfacial slip mechanism and reliable methods for deformation calculation are therefore essential to ensure the safe application of steel–shale ceramsite concrete composite beams.

Significant research has been conducted on interfacial slip in conventional steel–concrete composite beams, leading to important advances in connector models and slip calculation theories. However, the porous, lightweight nature of shale ceramsite concrete results in distinct stud interaction and bond–slip behavior compared with ordinary concrete, limiting the direct applicability of existing theories and design methods. Following the framework of “slip mechanism–calculation method–deformation characteristics,” this study reviews current research, identifies outstanding key issues, and underscores the importance of this work for theoretical and practical advancement.

II. CURRENT UNDERSTANDING OF INTERFACIAL SLIP MECHANISMS

The study of interfacial slip mechanisms aims to elucidate the initiation, progression, and evolution of slip, focusing primarily on the interaction between shear connectors and the surrounding shale ceramsite concrete. This section provides a systematic review from three aspects: material properties, stud force-transfer mechanisms, and the evolution of slip behavior.

2.1 Material Properties of Shale Ceramsite Concrete

Shale ceramsite concrete uses sintered shale ceramsite and ceramsite sand as aggregates. Its intrinsically porous and lightweight structure distinguishes it from conventional concrete and underlies the differences in its interfacial behavior. The density of shale ceramsite concrete is typically 60%–70% that of ordinary concrete, while its elastic modulus is about 70% of the latter [8]. This lower elastic modulus implies that under identical stress, shale ceramsite concrete undergoes greater deformation, which can lead to more pronounced initial interfacial incompatibility when deforming in conjunction with a steel beam.

The porous surface of the ceramsite aggregates and the characteristics of the interfacial transition zone (ITZ) between the aggregate and the cement paste influence the bond performance with the stud surface (or steel plate) [9]. Compared to the dense aggregate interface in ordinary concrete, the ITZ in shale ceramsite concrete is often weaker and exhibits distinct mechanical behavior, which directly affects the efficiency of interfacial shear transfer and the patterns of crack initiation and propagation [10]. Current research has predominantly focused on the macroscopic mechanical properties of the material, leaving the microscopic bond mechanisms and damage evolution processes at the steel–concrete interface insufficiently understood.

2.2 Force-Transfer Mechanism of Shear Studs

Shear studs are critical components for transferring interfacial shear in composite beams, and their force-transfer mechanism within concrete dictates the initiation and development of slip. For conventional or high-performance concrete, push-out test results [11,12] indicate that the load response of a stud typically progresses through elastic, elastoplastic, and failure stages. Common failure modes include shear yielding of the stud shank and crushing or splitting of the surrounding concrete. The shear capacity of a stud is closely related to the compressive strength of the concrete as well as the diameter and strength of the stud itself. The corresponding load–slip curve is often described using exponential or piecewise linear models [13].

While these mechanisms are well established for ordinary concrete, systematic studies on the behavior of studs embedded in shale ceramsite concrete remain scarce. The lower compressive strength and unique fracture toughness of shale ceramsite concrete—attributed to the "hinge effect" of its lightweight aggregates—may alter the failure mode of shear studs. Existing research suggests that the initial stiffness and ultimate slip of studs in lightweight aggregate concrete may differ from those in conventional concrete [14]. However, a clear understanding of concrete damage evolution, stud stress distribution, and their interaction throughout the entire loading process is still lacking. Consequently, no widely accepted model exists for predicting the bearing capacity and deformation of studs in this specific material.

2.3 Evolution of Interfacial Slip

Interfacial slip evolution arises from the interaction between shear stud forces and concrete deformation, influenced by multiple factors. For conventional composite beams, key parameters governing slip magnitude and distribution include stud diameter, aspect ratio, spacing (degree of shear connection), and concrete strength [15]. Generally, slip decreases with larger stud diameters or a higher degree of shear connection, while greater concrete strength enhances slip resistance [16,17]. When shale ceramsite concrete is used, these relationships may change. Given its lower elastic modulus and distinct failure mechanisms, interfacial slip can initiate earlier under identical stud configurations, and a lower load may be required to produce a given slip [18]. Moreover, shale ceramsite concrete typically exhibits greater shrinkage and creep than ordinary concrete, implying potentially more significant time-dependent slip under sustained loading—though research on this long-term effect remains sparse. Currently, limited experimental data on slip distribution and complete load–slip curves are available for steel–shale ceramsite concrete composite beams, hindering a systematic understanding of their slip evolution.

III. ADVANCES IN COMPUTATIONAL METHODS FOR INTERFACIAL SLIP

Accurate calculation of interfacial slip is crucial for the assessment and design of steel–shale ceramsite concrete composite beams. Current computational approaches primarily focus on two core issues: interfacial shear stiffness models and theories for slip quantification.

3.1 Theoretical Models for Shear Stiffness of Connectors

Shear stiffness, a key parameter linking interfacial shear force and slip, underpins all slip calculations. For ordinary concrete, shear stiffness models are primarily derived from experimental regression and theoretical analysis. Based on extensive testing, Nie et al. [19] proposed stiffness expressions that account for the full loading process of studs. Applying elastic-plastic foundation beam theory, Kuang et al. [20] modeled the constraint from surrounding concrete as equivalent springs, establishing a method for calculating the load-slip relationship and stiffness of studs, which offers clear mechanical interpretation. Qin et al. [16] developed a simplified analytical model to investigate stud shear stiffness under biaxial loading. The bilinear model proposed by Oehlers et al. [13] and the exponential model given in Eurocode 4 [21] are widely used empirical or semi-empirical models.

All the aforementioned models were developed based on the mechanical response of ordinary or high-strength concrete. The lower compressive strength, elastic modulus, and unique fracture toughness of shale ceramsite concrete result in a significantly different subgrade reaction coefficient (e.g., Winkler foundation modulus) compared to ordinary concrete. Directly substituting parameters for shale ceramsite concrete into existing models overestimates the constraint stiffness and consequently underestimates slip. Presently, no widely accepted theoretical model exists for stud shear stiffness that accounts for the porous and softening characteristics of shale ceramsite concrete. Although scholars like Ahmed et al. [14] have explored the shear behavior of novel connectors in lightweight concrete, their findings have not yet evolved into a general theoretical framework.

3.2 Analytical and Numerical Methods for Slip Calculation

Based on shear stiffness models, methods for calculating interfacial slip in composite beams can be categorized into analytical and numerical approaches. Analytical methods primarily involve solving differential equations that incorporate slip. For example, Ye et al. [22] applied the principle of minimum potential energy and variational calculus to derive theoretical solutions for interfacial slip under various loads. Sun et al. [23] employed a coefficient matrix method based on Timoshenko beam theory to analyze the influence of parameters such as connector stiffness and span-to-depth ratios on slip. These methods offer clear physical concepts but rely on multiple assumptions—such as linear elastic materials, uniform shear stiffness, and negligible concrete cracking—limiting their applicability to scenarios involving material nonlinearity, geometric nonlinearity, and complex loading. Furthermore, their formulas are often complex, hindering practical engineering application.

The finite element method is currently the primary numerical tool for studying the nonlinear behavior of interfacial slip. Common modeling strategies include:

- (1) Detailed Solid Model: Separate solid elements are used for the steel beam, concrete slab, and studs, with contact interfaces defined between studs and concrete [24]. This approach offers high accuracy but incurs significant computational cost and modeling complexity.
- (2) Composite Beam Element Model: The concrete slab and steel beam are modeled as beam elements, while studs are simplified as zero-length spring elements. Interface behavior is simulated by defining nonlinear load-slip constitutive relationships for the springs [25]. This method is computationally efficient, yet few publicly reported models have been specifically developed for shale ceramsite concrete.
- (3) Layered Beam Model: The composite beam cross-section is divided into layers along its height, with the nonlinear constitutive behavior of each material considered separately. This method, combined with the slip constitutive relationship of shear connectors, provides another efficient simplified analytical approach [26].

3.3 Design Provisions for Slip in Current Codes

Current design codes for steel–concrete composite beams, such as the Chinese GB 50017 [27], Eurocode 4 [21], and the American AISC specification [28], do not explicitly require direct calculation of interfacial slip. Instead, they control the influence of slip on strength and stiffness indirectly by specifying the degree of shear connection—the ratio of the number of studs provided to the number required for full shear connection.

These codes assume that for beams with full shear connection, the effect of slip on the ultimate moment capacity is negligible. For beams with partial shear connection, the flexural capacity is reduced accordingly. For serviceability deflection calculations, codes typically employ the transformed section method, which inherently neglects slip effects, or incorporate a generalized reduction factor to account approximately for the combined influence of concrete shrinkage, creep, and slip.

However, existing code provisions are primarily based on experimental and theoretical studies of conventional concrete composite beams. For shale ceramsite concrete composite beams, critical design parameters—including the appropriate degree of shear connection and the quantitative relationship between slip and the reduction in strength and stiffness—lack clear codified guidance. Furthermore, the distinctive long-term deformation characteristics of this material may render deflection calculation methods derived from ordinary concrete inadequate.

IV. DEFORMATION BEHAVIOR OF COMPOSITE BEAMS CONSIDERING SLIP EFFECTS

Interfacial slip not only directly affects shear transfer but also significantly influences the overall deformation of composite beams by altering the strain compatibility and internal force distribution across the section. Studying the deformation characteristics with slip effects is fundamental for evaluating serviceability, controlling deformation, and optimizing design.

4.1 Influence of Slip on Flexural Stiffness

Flexural stiffness is a core indicator of a composite beam's resistance to deformation, and interfacial slip is a major factor leading to its degradation. Under ideal full-composite action, the steel beam and concrete flange share the same curvature. When interfacial slip occurs, the two components undergo different longitudinal deformations, causing the actual neutral axis of the concrete slab to be lower than that of the steel beam. This reduces the concrete's contribution to the overall sectional moment of inertia. This effect introduces "deformation incompatibility," resulting in greater curvature for the same applied moment and, macroscopically, a reduction in the effective flexural stiffness EI_{eff} .

Research indicates that the degree of shear connection η is the most critical parameter affecting stiffness degradation. The lower η is, the more pronounced the slip and the greater the stiffness reduction [29]. Additionally, the elastic modulus of the concrete (the lower modulus of shale ceramsite concrete exacerbates this effect), the load level (as loading increases and materials enter the nonlinear range, stiffness degradation accelerates), and the shear stiffness of the studs (affecting the rate of slip development) all significantly influence the stiffness degradation pattern [30,31]. Numerical studies by Mirambell et al. [32] confirmed significant errors in some code-based estimations of serviceability deflections when slip is considered.

4.2 Deflection Calculation Theory Considering Slip Effects

Accurately calculating the deflection of composite beams, particularly at the mid-span of simply supported members, is crucial for serviceability limit state design. The primary approaches for deflection calculation considering slip effects are as follows:

(1) Analytical Correction Method

This method introduces an additional deflection component caused by slip into classical deflection formulas derived from material mechanics (e.g., based on the transformed section method). A common theoretical approach involves integrating the interfacial slip strain along the beam length to obtain the additional curvature induced by slip, from which the extra deflection is computed. Ye and Han et al [22, 33] have derived corresponding analytical or semi-analytical solutions for different types of composite beams using energy methods or differential equations. However, these formulas are often complex, rely on specific assumptions regarding slip distribution and constitutive models, and are therefore difficult to apply directly in practical engineering.

(2) Effective Stiffness Reduction Method

This is a more practical engineering approach. Its core idea is to account for slip effects through a stiffness reduction factor ψ [34]. The factor ψ , typically a function of the degree of shear connection η , can be determined by regression of experimental data or parametric numerical analysis. While several empirical formulas exist for conventional concrete composite beams, research on ψ specifically for shale ceramsite concrete composite beams is nearly absent. Due to the material's nonlinear characteristics, ψ may depend not only on η but also on concrete strength and load magnitude.

(3) Numerical Integration Method

After obtaining the bending moment distribution along the beam and establishing a moment-curvature ($M-\phi$) relationship that incorporates slip effects, deflection is calculated by performing double numerical integration of the curvature. The key to this method lies in developing an accurate $M-\phi$ model that considers both slip and material nonlinearity. Researchers such as Wang et al. [35] have applied this approach in studies on recycled aggregate concrete or continuous composite beams, but its application to shale ceramsite concrete requires further investigation.

V. MAJOR ISSUES AND CURRENT RESEARCH CHALLENGES

5.1 Unclear Interfacial Slip Mechanism

While existing research confirms that interfacial slip leads to stiffness degradation and increased deformation, a deep understanding of the underlying physical and mechanical mechanisms remains lacking. The core difficulty lies in the disconnect between macroscopic observations and microscopic behavior. Current knowledge largely relies on classical theories developed for ordinary concrete, failing to fully capture how the porous and heterogeneous nature of shale ceramsite concrete fundamentally alters force transfer paths and damage evolution modes (e.g., aggregate crushing, interfacial transition zone failure). Consequently, establishing a quantitative link from meso-scale damage to macro-scale slip constitutive behavior has not been achieved, which fundamentally hinders the development of accurate theoretical models.

5.2 Gap between Theoretical Models and Practical Application

A major bottleneck is the absence of dedicated computational models. Existing load-slip constitutive models for studs and analysis theories for composite beams were developed for ordinary concrete and cannot accurately represent the constraint-softening effect in shale ceramsite concrete. Furthermore, simplified yet practical analysis methods that balance computational efficiency and accuracy—such as specialized composite beam elements incorporating coupled material nonlinearity and slip—are still underdeveloped. Predictive models for slip behavior under complex conditions like long-term shrinkage and creep, fatigue, or seismic loading are virtually nonexistent, severely limiting accurate analysis and design application of this structural system.

5.3 Absence of Design Code Support

From an engineering practice perspective, the most significant barrier is the lack of standardized design provisions. Current major structural design codes worldwide contain no specific clauses for steel-shale ceramsite concrete composite beams. This leaves critical design aspects—such as shear connection design, deflection verification considering slip, and seismic performance assessment—without codified guidance. The absence of established basic design parameters and performance-based criteria seriously impedes the standardized promotion and practical application of this green, high-performance structural system.

VI. CONCLUSION

- (1) Interfacial slip in steel-shale ceramsite concrete composite beams significantly reduces their overall stiffness and increases deformation, representing a fundamental mechanical challenge to their safety and serviceability.
- (2) Due to the porous and lightweight nature of shale ceramsite concrete, the interaction mechanism with shear studs, the interfacial damage evolution, and the progression of slip differ fundamentally from those in conventional concrete composite beams.
- (3) Current load-slip constitutive models for studs, slip calculation theories, and mainstream design codes—developed primarily for ordinary concrete—suffer from mechanistic inconsistency and insufficient predictive accuracy when applied to steel-shale ceramsite concrete composite beams.
- (4) Major design codes (e.g., Chinese, European, and American) control the effect of slip on ultimate strength indirectly by specifying a degree of shear connection, while approximating its influence on deformation through stiffness reduction factors or the transformed section method.

To address these challenges, future work should prioritize: 1) employing multi-scale methods to deepen the understanding of interfacial slip mechanisms; 2) developing dedicated constitutive models and efficient analytical methods that reflect the unique properties of shale ceramsite concrete; and 3) advancing the formulation of design standards and guidelines to support its standardized engineering application.

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