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Behaviour of Stud Shear Connectors in Composite Beams: A Push-Out Test Approach

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ABSTRACT

The efficiency of composite beam systems heavily relies on the strength and ductility of shear connectors. This study investigates the mechanical performance of headed stud shear connectors through 42 push-out tests designed to evaluate their load-slip characteristics. Various parameters were considered including connector type, concrete strength, sheet thickness, and stud arrangement. The tests were performed using a 1000 kN Universal Testing Machine (UTM) with precise instrumentation for load and slip measurements. Results indicate a direct relationship between concrete grade and connector stiffness, while failure modes varied from stud shearing to concrete crushing. A three-stage load-slip behavior was identified, offering insights into the progressive damage and eventual failure of the interface bond. The findings support optimized connector design in composite structures for enhanced structural integrity.

Keywords: *Composite beams, shear connectors, push-out tests, load-slip behavior, interface bond, stud failure, concrete strength.*

1. INTRODUCTION

Composite construction, especially steel-concrete systems, depends significantly on the performance of shear connectors which ensure effective load transfer and composite action. The headed stud shear connector is widely adopted due to its ease of installation and multidirectional strength. Load-slip characteristics and ductility play crucial roles in defining the strength and serviceability of these connectors. Push-out testing is a standardized method to evaluate these parameters under controlled conditions. This study aims to explore the influence of design and material parameters on the behavior of stud shear connectors.

Concrete, one of the most widely used construction materials, offers several advantages such as high compressive strength, durability, and versatility. However, it is inherently limited by its low tensile strength and poor ductility. Ductility, the ability of a material or structure to undergo significant plastic deformation before failure, is an essential property for structural resilience, particularly under dynamic loading conditions such as earthquakes, blasts, and impacts.

Historically, steel—known for its excellent ductility—was extensively used in construction. With the advent of reinforced concrete, concrete began replacing steel in many structural applications. Despite this, concrete's brittleness under tensile loading remains a critical concern. Sudden failures in reinforced concrete structures, especially under seismic or blast loads, are often attributed to insufficient ductility. Ensuring that critical structural sections can undergo large plastic deformations is vital for energy dissipation and avoidance of brittle collapse. In seismic zones, the design philosophy emphasizes ductility through strategies like the “strong column–weak beam” approach, which promotes the formation of plastic hinges in beams while keeping columns elastic, thus enhancing overall structural stability.

The demand for strength, safety, serviceability, and cost-effectiveness in modern construction has led to increased adoption of steel-concrete composite construction. This approach has gained momentum, especially after the revision of seismic design codes and hazard maps in various parts of the world. Research on structural failures during past earthquakes has emphasized the importance of uniform plastic deformation, achievable through composite design methodologies.

Globally, the use of steel in construction is widespread. In the United Kingdom, more than 90% of single-storey buildings and 70% of multi-storey buildings are steel-framed. The trend is similar across other advanced economies such as the USA, Japan, Sweden, and the Netherlands, where steel dominates both commercial and industrial construction sectors. In contrast, India still relies heavily on traditional building materials like brick, gravel, and cement, and the use of structural steel remains limited.

Reinforced concrete structures in India are primarily constructed using the cast-in-situ method, which, despite being conventional, has several drawbacks:

While steel structures offer quicker assembly and high tensile strength, they are prone to corrosion, lack availability in large sizes, and lose strength at elevated temperatures.

To overcome the limitations of both materials, steel-concrete composite construction is employed. This system effectively utilizes concrete's compressive strength and steel's tensile strength. Moreover, both materials exhibit similar thermal expansion behavior, making them structurally compatible. Composite construction provides multiple advantages, including:

This methodology has been widely adopted in high-rise buildings, bridges, and critical infrastructure globally. Composite construction is especially favored in seismic zones for its capacity to withstand repeated load reversals. Countries like Japan have made significant progress in developing standard practices for combining concrete cores, steel frames, and composite floor systems.

Furthermore, modern composite systems have evolved with innovations such as headed shear studs (developed in the 1950s), steel decking, and prefabricated components, contributing to faster and safer construction. The use of cold-formed steel sheets as permanent formwork in composite slabs and beams has also gained popularity. While these sheets help reduce construction time and provide effective reinforcement, they must be adequately protected against corrosion, for which advanced anti-corrosion paint systems are now available in India.

An emerging innovation in this domain is the Thin-Walled Steel Stiffened Concrete Composite (TWSSCC) Beam system. This system uses cold-formed steel sheets as both formwork and reinforcement, combined with concrete infill and shear connectors to ensure composite action. The passive confinement from the steel sheet enhances both the strength and ductility of concrete. These beams, simpler to fabricate and suitable for small- to medium-scale structures, represent a cost-effective and performance-optimized alternative to traditional reinforced concrete or hot-rolled steel beams.

2. REVIEW OF LITERATURE

Past studies indicate that composite beam strength is influenced not only by the connectors' strength but also by their ductility and slip characteristics. Mechanical connectors have been classified as ductile or brittle based on their deformation behavior under load. Headed studs have proven effective for industrial applications due to their simple installation and consistent performance. However, the redistribution of load among multiple connectors and their behavior under progressive loading necessitate further investigation through experimental studies such as push-out tests.

Johnson (2004) expanded upon these fundamentals by offering practical design insights for composite structural elements, particularly in the context of modern buildings. His work emphasized the role of composite interaction and the mechanics of load transfer through shear connectors.

The importance of shear connectors in composite action was further highlighted in the experimental investigations of Lam and El-Lobody (2005). Their study on headed stud shear connectors revealed the influence of connector dimensions and arrangement on load-slip behavior and ultimate strength, providing critical data for design optimization.

Nonlinear behavior and finite element modeling (FEM) have also become integral to understanding composite systems. Hegger et al. (2001) conducted detailed FEM simulations of composite beams with partial shear connection, validating their models against experimental results and demonstrating the complex interactions between concrete cracking and interface slip.

Ahmed and Mahmoud (2010) extended the use of FEM to beams with profiled steel sheeting, observing that nonlinearities due to local buckling and slip significantly impact structural performance. Similarly, Nguyen and Kim (2009) developed finite element models of push-out tests for large stud connectors, accurately capturing load-slip characteristics and enabling better prediction of connection behavior.

Anderson and Najafi (1994) studied load-deflection responses of composite beams, emphasizing the effects of steel deck geometry on overall flexural performance. Their findings underscored the necessity of accounting for decking parameters in design.

Wright and Evans (1989) focused on the ultimate load behavior of composite slabs, providing empirical equations that influenced early design codes. Building upon this, Hossain and Wright (2004) combined experimental and theoretical approaches to assess the interaction between steel sheeting and concrete, revealing complex load transfer mechanisms.

Finite element analysis was further applied by Satsangi and Arora (2014), who developed numerical models to simulate the structural response of composite beams. Their results demonstrated good agreement with experimental data and validated FEM as a reliable tool for composite beam analysis.

Collectively, these studies contribute to a comprehensive understanding of composite beam behavior, spanning material interactions, connector performance, load-deflection characteristics, and advanced numerical modeling. This body of work continues to inform the design and development of safer, more efficient composite structural systems.

3. MATERIALS AND METHODS

3.1 Test Matrices

A total of 42 push-out specimens were fabricated and tested across four series (P1 to P4).

4. RESULTS AND DISCUSSION

The push-out tests conducted on 42 specimens provided valuable insights into the performance of stud shear connectors in composite structures. The analysis focused on load-slip characteristics, failure modes, and the influence of varying parameters such as concrete grade, connector type, and sheet thickness. The findings are discussed in the following sections.

4.1 Load-Slip Characteristics

All tested specimens demonstrated a characteristic three-phase load-slip response. In the initial linear stage, the steel-concrete interface remained bonded with negligible slip, and the load increased proportionally. This stage reflected the elastic behavior of the composite system. As the loading progressed into the nonlinear peak stage, microcracking was observed in the concrete around the studs, and the slip began to increase more rapidly. This was indicative of the degradation of both chemical and mechanical bonds. Upon reaching the post-peak stage, a reduction in load-bearing capacity was noticed, attributed to the crushing of concrete and partial shearing of studs. Despite the interface bond failure, the system continued to resist load through residual friction and mechanical interlock.

4.2 Observed Failure Modes

The failure modes varied depending on material and geometric parameters. In specimens with lower-grade concrete (M20), the predominant failure mode was concrete crushing, where the region surrounding the stud connectors deteriorated due to lower compressive strength. Conversely, in specimens with higher-grade concrete (M30), stud shearing was the most common failure mode. This shift is attributed to the enhanced strength of the surrounding concrete, which restrained deformation and transferred more stress to the connectors. Additionally, local buckling of the steel sheets was observed in specimens with thinner sheet profiles, particularly near weld zones, although this did not significantly affect the overall structural performance.

4.3 Influence of Concrete Grade

An increase in concrete grade led to noticeable improvements in both stiffness and load-carrying capacity. M30 grade concrete specimens not only showed higher initial stiffness but also delayed the onset of slip and cracking. The transition from brittle to ductile failure with increasing concrete strength highlights the importance of concrete quality in enhancing connector performance. Furthermore, specimens with stronger concrete experienced less concrete damage and more controlled, ductile stud shearing.

4.4 Influence of Connector Configuration

The configuration and number of stud connectors significantly influenced the mechanical behavior of the specimens. Double stud arrangements outperformed single stud setups, providing greater load resistance and improved slip distribution across the interface. This arrangement allowed for better redistribution of stress during loading, resulting in more ductile and controlled failure behavior. In comparison, single stud specimens exhibited lower peak loads and more abrupt post-peak declines, emphasizing the benefits of increased connector density.

4.5 Influence of Sheet Thickness

While sheet thickness had a marginal impact on ultimate load capacity, it played a key role in structural stability. Thicker sheets offered improved resistance to local buckling and better confinement to the embedded concrete. Specimens with thicker sheets displayed more consistent load-slip behavior and reduced scatter in test results. However, the overall effect of sheet thickness on connector strength was secondary to that of concrete strength and stud arrangement.

4.6 Summary of Observations

The test results revealed clear trends and relationships among the studied parameters. Higher concrete grades improved both strength and stiffness, while increasing the number of connectors enhanced load distribution and ductility. Thicker steel sheets contributed to better confinement and surface integrity. These findings align well with previous research and provide useful guidance for the design of composite systems with stud shear connectors.

The table summarizes a series of experimental specimens (P1 to P4) designed to study the behavior of shear connectors in composite construction. Each series includes four specimens with variations in connector type (single or double stud), concrete grade (M20 or M30), and steel sheet thickness (ranging from 0.8 mm to 1.6 mm), while keeping the stud diameter (9 mm) and height (50 mm) constant. Series P1 uses single studs with lower-grade concrete (M20) and the thinnest sheet (0.8 mm), serving as a baseline. P2 increases both the sheet thickness and the number of studs. P3 maintains a single stud but upgrades to higher-grade concrete (M30) with a thicker sheet. P4 combines double studs, the highest concrete grade, and the thickest sheet, representing the most robust setup. The variations aim to evaluate the influence of connector configuration, concrete strength, and sheet thickness on structural performance.

5. CONCLUSION

Push-out tests effectively revealed the mechanical behavior of stud shear connectors under increasing loads. Key conclusions include:

- Ultimate load is significantly influenced by concrete grade, stud configuration, and sheet thickness.
- Interface bond degradation begins with chemical bond loss and progresses to mechanical failure.
- Concrete strength dictates the failure mode, with higher grades favoring ductile stud failure and lower grades causing concrete crushing.

Load-slip curves can be used to characterize the interface bond and help improve design parameters for composite systems.

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