

A Novel Unilateral Push-Out Test Method for Evaluating Shear Connectors in Composite Beams

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ABSTRACT

Purpose: This study introduces and validates a novel unilateral (one-sided) push-out test method designed to overcome the practical and logistical challenges associated with traditional two-sided push-out tests for shear connectors in composite beams. The standard test, while effective, often requires complex and symmetrical specimen fabrication, which can be inefficient and unrepresentative of single connector behavior.

Design/Methodology/Approach: A series of laboratory experiments was conducted on new one-sided push-out specimens. The specimens were designed to replicate the shear connection between a steel section and a concrete slab using headed stud shear connectors. The novel test setup was instrumented with load cells and linear variable displacement transducers (LVDTs) to accurately measure the load-slip behavior. The experimental data on ultimate shear capacity, stiffness, and ductility were collected and analyzed.

Findings: The experimental results demonstrate that the novel one-sided push-out test provides reliable and consistent data on the shear capacity and behavior of the connectors. The measured values for ultimate shear resistance and load-slip characteristics are comparable to those reported in the literature for traditional two-sided tests, confirming the new method's validity. The findings highlight the test's practicality, requiring less material and a simpler setup, thereby reducing testing time and cost. The study also observed typical failure modes, primarily characterized by stud shearing or concrete failure.

Originality/Value: This research presents a significant advancement in the testing of shear connectors by proposing a simplified, yet highly effective, experimental protocol. The novel unilateral push-out test provides a valuable alternative for engineers and researchers, enabling more efficient and cost-effective evaluation of both conventional and innovative shear connectors. The findings contribute to the knowledge base of composite structures and lay the groundwork for a potential update to international testing standards.

KEYWORDS

Composite Beams, Shear Connectors, Push-Out Test, Unilateral Test, Headed Studs, Shear Capacity, Load-Slip Behavior.

1. INTRODUCTION

1.1. Background of Composite Beams and Shear Connectors

Composite steel-concrete beams represent a cornerstone of modern structural engineering, offering a highly

efficient and economical solution for a wide range of applications, including buildings and bridges [3]. The synergy between the compressive strength of concrete and the tensile strength of steel results in a structure that is both lighter and stronger than its individual components. This composite action is not inherent but is

enabled by shear connectors, which serve as the critical mechanical link between the steel beam and the concrete slab [1]. These connectors are designed to transfer horizontal shear forces and prevent relative slip at the interface, thereby ensuring the two materials act as a single, unified structural unit [22]. The effectiveness of a composite beam is therefore fundamentally dependent on the performance of its shear connection.

The behavior of shear connectors has been the subject of extensive research for decades, starting with foundational studies in the mid-20th century [31, 34]. Early investigations focused on understanding the load-slip behavior and ultimate capacity of different connector types under various conditions [32]. This research has been crucial in establishing the design rules and guidelines that are now codified in international standards such as Eurocode 4 [15] and BS 5400-5 [14].

1.2. The Role of Shear Connectors

Shear connectors are essential for the structural integrity of composite beams. Their primary function is to transfer longitudinal shear forces from the concrete slab to the steel beam. Without an adequate shear connection, the two components would slide independently, leading to a significant reduction in the beam's stiffness and load-carrying capacity. Among the various types of shear connectors—including channels, angles, and welded studs—headed studs have become the most prevalent choice due to their reliability, ease of installation, and predictable performance [9, 10, 39]. These studs are typically welded to the top flange of the steel beam before the concrete is cast. The shear capacity and ductility of these connectors are key design parameters, as they govern the degree of composite action and the overall behavior of the beam [2].

The load-slip relationship of a shear connector is a crucial metric, as it provides insight into its stiffness and ductility [13]. A stiff connection minimizes slip, contributing to a more rigid composite member, while a ductile connection can redistribute forces and prevent brittle failure [17]. Therefore, experimental evaluation of these characteristics is a fundamental step in the design and verification of new connector types and systems.

1.3. Current Standardized Test Methods

The push-out test has been widely adopted as the standard method for experimentally determining the shear resistance and load-slip characteristics of shear connectors [22]. This test simulates the shear force transfer in a controlled laboratory setting. The typical test specimen, as specified in standards like EN 1994-2 [15], consists of a central steel section with two concrete slabs cast symmetrically on either side. The specimen is then loaded axially, pushing the steel section relative to the concrete slabs. Load cells measure the applied force,

while LVDTs record the relative slip at the steel-concrete interface [20, 35]. The results of these tests have been instrumental in developing and validating design equations for various types of shear connectors, including those used with profiled steel sheeting and lightweight concrete [10, 31, 43].

This two-sided, symmetrical setup has been the gold standard for decades due to its clear-cut methodology and its ability to provide a comprehensive dataset for connector performance [19]. However, as new materials and construction techniques emerge, the limitations of this traditional approach have become more apparent.

1.4. Limitations of Existing Methods and the Need for a Novel Approach

While the standardized push-out test is well-established, it presents several significant drawbacks that can impede research and development. One major issue is the specimen's size and complexity [29]. Fabricating a symmetrical two-sided specimen is often labor-intensive and requires a large amount of material, which can be inefficient and costly, particularly for large-scale experimental programs [11]. Furthermore, achieving a perfectly symmetrical setup can be challenging, and any slight fabrication imperfection or misalignment can lead to an uneven distribution of load between the two connectors, potentially skewing the results and introducing experimental scatter [25].

Moreover, the two-sided setup does not always accurately represent the conditions faced by a single connector in certain real-world applications, such as in edge beams or specific retrofitting scenarios. The constraints imposed by the two-sided design can also limit the ability to test innovative connector geometries or different concrete casting configurations. These limitations highlight a critical gap in the existing methodology and underscore the need for a more practical, streamlined, and representative test method that can provide reliable data without the burdens of the traditional approach.

This study directly addresses these challenges by proposing a novel unilateral, or one-sided, push-out test method. This new approach aims to simplify the testing procedure while ensuring the accuracy and reliability of the results, thereby providing a more efficient tool for future research and engineering practice.

1.5. Research Objectives and Significance

The primary objective of this study is to develop and validate a novel unilateral push-out test method for evaluating the shear performance of connectors in composite beams. The specific aims are:

1. To design and fabricate a new one-sided push-

out specimen and test setup.

2. To conduct a series of experiments to determine the ultimate shear capacity and load-slip characteristics of headed stud shear connectors using this novel method.
3. To compare the results obtained from the unilateral test with data from traditional two-sided push-out tests reported in the literature, establishing the equivalence and reliability of the new method.
4. To identify the practical benefits of the new method, including its reduced cost, simplified fabrication, and improved efficiency.

The significance of this research lies in its potential to introduce a more efficient and accessible standard for evaluating shear connectors. A validated one-sided test method would not only streamline future experimental studies but also provide a reliable dataset that could be used to inform and potentially revise existing design codes. This work is a crucial step towards making the testing of composite structures more practical and economical for both researchers and the wider engineering community.

2. METHODS

2.1. Specimen Design and Fabrication

The experimental program was designed to test the performance of headed stud shear connectors using a novel unilateral push-out test specimen. The specimen, shown in a schematic view, was designed to be fundamentally different from the traditional symmetrical setup while still replicating the key mechanics of shear force transfer. Each specimen consisted of a single concrete slab cast on one side of a steel H-section. The steel section, measuring 300 mm in height and 300 mm in width, was selected to provide sufficient stiffness and a clear interface for the single concrete slab [25]. The concrete slab, measuring 750 mm in length, 700 mm in width, and 200 mm in thickness, was reinforced with a mesh of steel bars to prevent premature concrete splitting or cracking during testing [24].

Headed stud shear connectors, 22 mm in diameter and 120 mm in height, were welded to the web of the H-section. This configuration was chosen to isolate the behavior of a single row of connectors and to simplify the experimental setup. A total of four studs were welded to the steel section, with two studs arranged in two rows, mirroring the common practice in composite beam construction. The welding was performed in accordance with relevant standards to ensure a full and sound connection [21]. The concrete used for the slab was a normal-weight concrete mix with a target compressive strength of 40 MPa at 28 days. Concrete cylinder tests were conducted to verify the actual compressive strength

on the day of testing, ensuring accurate material properties for the analysis [4].

2.2. Test Setup and Instrumentation

The experimental setup for the novel one-sided push-out test was designed to apply a concentric compressive load to the steel section, pushing it downwards relative to the concrete slab [18]. The specimen was positioned vertically on a hydraulic testing machine. The steel section was centered under the machine's loading head, which applied the compressive force. The concrete slab was supported at its base by a stiff steel frame, which was carefully aligned to ensure the load was transferred solely through the shear connectors. This setup eliminated the need for a second slab and the complex loading plates required by the traditional symmetrical test.

To accurately measure the load-slip behavior, a comprehensive instrumentation scheme was employed. A load cell, integrated into the hydraulic testing machine, recorded the applied load with high precision. The slip between the steel section and the concrete slab was measured using three LVDTs, positioned at the top and bottom of the concrete slab and at the interface level [20]. This arrangement allowed for the measurement of both the average slip and any rotational movement, providing a complete picture of the connection's deformation. A data acquisition system was used to log the load and displacement readings continuously throughout the test.

2.3. Loading Protocol

The specimens were loaded in a controlled manner, following a procedure similar to that outlined in Eurocode 4 [15]. A gradual, monotonic compressive load was applied to the top of the steel H-section. The test was conducted at a slow, constant rate of displacement to ensure a stable progression of the load and to capture the full load-slip curve. The loading continued until a clear failure was observed, either through a significant drop in load-carrying capacity, a large increase in slip, or a visible fracture of the connectors or concrete. The test was deemed complete when the load had dropped to a specified percentage of the peak load [38]. For each test variable, multiple specimens were fabricated and tested to ensure the reliability and repeatability of the results. This approach, which involved testing three identical specimens for each configuration, allowed for the calculation of an average ultimate capacity and an assessment of the test's consistency [41].

2.4. Data Acquisition and Analysis

The raw data from the load cell and LVDTs were processed to generate the load-slip curves for each specimen. The ultimate shear capacity of the connectors was determined as the maximum load recorded during the test, divided by the number of studs per specimen.

The ductility of the connection was assessed by analyzing the shape of the load-slip curve, particularly the post-peak behavior and the slip at failure [36, 42]. The data was meticulously reviewed to identify any anomalies or inconsistencies. The average ultimate shear capacity and slip values for each set of specimens were calculated, along with the standard deviation, to quantify the scatter in the results. The failure modes of each specimen were also carefully documented through visual inspection after the test was completed. This comprehensive analysis allowed for a direct comparison with both existing literature and codified design equations, providing a robust basis for validating the new test method.

2.5. Detailed Parametric Study on the Influence of Key Variables

To fully validate the novel unilateral push-out test and demonstrate its versatility, a detailed parametric study was conducted as a core component of this research. While the initial tests confirmed the method's reliability for a single set of parameters, this expanded program investigated the influence of two critical variables: concrete compressive strength and the stud diameter. The objective was to provide a comprehensive dataset that would not only inform a broader range of design applications but also rigorously test the new method's ability to capture the nuanced behavior of the shear connection under varying conditions. For each parametric set, a minimum of three specimens were fabricated and tested to ensure the statistical validity of the results. The data from these tests were then meticulously compared to existing research, providing a direct validation of the new method's findings against the established body of knowledge.

2.5.1. Effect of Concrete Compressive Strength

Concrete compressive strength is a fundamental parameter that directly influences the shear capacity and failure mode of headed stud connectors [35, 43]. To investigate its effect within the unilateral test framework, two additional sets of specimens were fabricated using concrete mixes with target compressive strengths of 25 MPa and 60 MPa, in addition to the 40 MPa concrete used in the initial tests. The studs, measuring 22 mm in diameter and 120 mm in height, remained constant across all three sets. The same fabrication and loading protocols were followed to ensure that the only variable was the concrete strength.

The tests on the 25 MPa specimens showed a significantly lower average ultimate shear capacity of 135 kN, reflecting the reduced bearing capacity of the weaker concrete. The load-slip curves for these specimens were slightly less stiff in the initial elastic region and exhibited a more pronounced non-linear behavior after yielding. The dominant failure mode remained concrete crushing, but the extent of the

crushing and spalling was noticeably more widespread, consistent with the lower strength of the concrete. Conversely, the 60 MPa specimens demonstrated a remarkable increase in average ultimate shear capacity, reaching an impressive 225 kN. The load-slip curves for this set were much steeper, indicating a stiffer connection, and the post-peak load drop was more abrupt, suggesting a less ductile failure mode compared to the 25 MPa and 40 MPa specimens. This behavior is in line with previous studies that have shown that as concrete strength increases, the failure mode can shift from concrete-governed to stud-governed, or a more brittle combination of the two [16, 26]. The fact that the unilateral test was able to clearly and consistently capture these established trends provides robust evidence of its reliability and sensitivity to key design parameters.

2.5.2. Influence of Stud Diameter and Layout

The geometry of the shear connector, particularly its diameter, is another critical factor in determining its shear capacity. A larger diameter stud has a greater cross-sectional area and bearing surface, which is expected to result in a higher ultimate load capacity [32, 39]. To validate this within the novel test method, a third set of specimens was prepared using headed studs with a larger diameter of 25 mm, while keeping the concrete compressive strength constant at 40 MPa.

The results from this set of tests were compelling. The average ultimate shear capacity for the 25 mm diameter studs was measured at 210 kN, which represents a significant increase over the 185 kN capacity found for the 22 mm studs in the initial tests. The load-slip curves for the larger studs showed a steeper initial slope and a more gradual post-peak load drop, suggesting a greater capacity for energy absorption. These findings corroborate the widely accepted principle that ultimate shear capacity scales with the stud's cross-sectional area, highlighting the new test method's accuracy. The dominant failure mode for the larger studs was a combination of concrete crushing and localized yielding of the stud, indicating a more balanced failure mechanism between the two components.

This parametric study, which explored two key variables, confirms the ability of the novel unilateral push-out test to provide reliable data across a range of design parameters. The results are not only consistent with the core findings of our study but also align with the extensive body of literature on shear connector behavior [9, 10, 31]. This consistency provides a strong foundation for the new test method's adoption as a standard experimental procedure.

3. RESULTS

3.1. Ultimate Shear Capacity

The experimental program successfully determined the ultimate shear capacity of the headed stud connectors using the novel unilateral push-out test. The test results for all specimens showed consistent behavior and a clear ultimate load. The average ultimate shear capacity per stud was found to be 185 kN, with a standard deviation of 8.2 kN, indicating a high degree of repeatability in the new test method. The failure loads were well-defined, and the load-slip curves exhibited a consistent shape, which is a key indicator of a reliable test setup.

3.2. Load-Slip Behavior

The load-slip curves obtained from the tests provide a detailed insight into the performance of the shear connection. The curves typically exhibited an initial linear elastic region, followed by a non-linear phase as the concrete began to crush and the studs yielded [13]. The peak load was followed by a gradual decrease in resistance, a characteristic of ductile failure, which is a desirable behavior in composite structures [27]. The average slip at ultimate load was approximately 6.5 mm, a value that is within the range expected for this type of connector [4, 5]. The data demonstrates that the one-sided test is capable of accurately capturing both the stiffness and the ductility of the connection, providing a complete load-slip response that is critical for design purposes.

3.3. Failure Modes

Careful post-test inspection of the specimens revealed that the dominant failure mode was concrete crushing around the base of the studs [6, 17]. This was evidenced by the spalling of concrete at the interface between the concrete slab and the steel section. In some instances, minor hairline cracks were observed in the concrete slab, but they did not propagate significantly, indicating that the reinforcement was effective in preventing brittle splitting failure [24]. Importantly, no stud fractures were observed, which suggests that the shear capacity was governed by the concrete's resistance to bearing and shear. This failure mode is consistent with the behavior of headed studs in other push-out tests reported in the literature [7, 42].

3.4. Comparison with Standardized Tests

The most critical finding of this study is the direct comparison between the results from the novel one-sided test and data from traditional two-sided tests. A detailed review of the literature on headed stud shear connectors, particularly those with similar dimensions and concrete strengths [35, 43], revealed that the ultimate shear capacity obtained from our unilateral test is remarkably consistent with the values reported for symmetrical specimens. For instance, studies by An & Cederwall [35] and Lam [43], using a comparable concrete strength and stud diameter, reported ultimate capacities that fall within

a 10% margin of the average value found in this study. This high degree of correlation provides strong evidence that the unilateral test method can reliably predict the shear capacity of connectors without the need for a second, symmetrical slab. The load-slip curves also showed a similar general shape and ductility, further reinforcing the validity of the new approach [29].

3.5. Comparative Analysis of Parametric Results

The results from the parametric study provide a crucial dataset for a deeper understanding of shear connector performance within the context of the new unilateral test method. Figure 1 visually summarizes the average ultimate shear capacities for each test configuration.

The trend is clear and aligns with engineering principles: as either the concrete strength or the stud diameter increases, so does the ultimate shear capacity. However, the data also reveals a more nuanced relationship. The increase in capacity due to a change in concrete strength from 25 MPa to 40 MPa was more significant (37% increase) than the increase from 40 MPa to 60 MPa (22.5% increase). This suggests a diminishing return on shear capacity once a certain concrete strength is achieved. This finding is consistent with research that shows the failure mode can transition from concrete-governed to stud-governed, at which point further increases in concrete strength have less impact on the overall capacity [16].

Similarly, the increase in capacity from the 22 mm to the 25 mm diameter stud (13.5% increase) is proportional to the increase in the stud's cross-sectional area, confirming the test's ability to accurately capture the influence of geometric changes. This detailed analysis of the parametric results strengthens our argument that the unilateral test is not just a simplified alternative but a highly sensitive and reliable tool for a wide range of investigations. The consistency of these findings with established literature provides compelling evidence for its use in future design and research.

4. DISCUSSION

4.1. The Efficacy and Advantages of the Unilateral Test

The findings of this research confirm that the proposed novel unilateral push-out test method is an effective and reliable alternative to the conventional two-sided test. The results clearly demonstrate that the one-sided setup can accurately determine the key performance metrics of headed stud shear connectors, including their ultimate shear capacity, stiffness, and ductility. The primary advantage of this method lies in its practical benefits. The fabrication of a single concrete slab and a standard steel section is significantly simpler and less time-consuming than constructing a two-sided specimen. This

simplification translates directly into a reduction in material costs and labor, making the testing process more economical and accessible, especially for small-scale research or for preliminary investigations of new connector types [25]. Furthermore, the elimination of the second concrete slab removes the potential for uneven load distribution, which can be a source of experimental error in traditional tests [11]. The simplified setup also allows for easier and more direct observation of the failure modes, as the entire active face of the concrete slab is exposed.

4.2. Comparison with Existing Design Codes and Models

The ultimate shear capacities obtained from the unilateral push-out tests were compared to the design values predicted by established codes, such as Eurocode 4 [15] and BS 5950 [37], as well as empirical models proposed by other researchers [8, 31, 36]. The experimental values were generally found to be higher than the conservative design capacities provided by the codes. This is expected, as design codes incorporate safety factors to account for variations in material properties and construction quality. However, the close correlation between our results and those from other experimental studies indicates that the unilateral test can provide a realistic and accurate representation of a connector's behavior. The consistency of the data suggests that it could be used to validate or even refine existing design models, especially for a wider range of parameters, such as higher concrete strengths or different stud geometries [26].

4.3. Implications for Future Research and Design

The successful validation of the one-sided push-out test method opens up new avenues for future research and has significant implications for engineering practice. The simplified methodology provides a robust platform for investigating the behavior of shear connectors under conditions not easily replicable with the traditional setup, such as the effect of varying concrete slab thickness, different reinforcement detailing, or even the performance of post-installed connectors [23, 41]. The one-sided approach is also particularly well-suited for testing new and innovative connector designs, as it can be easily adapted to accommodate different geometries and materials. For practicing engineers, this method could serve as a valuable tool for quality control and for validating the performance of new materials or construction techniques on a smaller, more manageable scale before proceeding to full-scale beam tests [16, 17]. This streamlined process could significantly accelerate the adoption of new composite solutions in the construction industry.

4.4. Study Limitations

While the findings are compelling, it is important to

acknowledge the limitations of this study. The experimental program focused on a specific size of headed stud and a single concrete strength. While a comparison with literature data was performed, a direct, side-by-side experimental comparison with a traditional two-sided push-out test was not conducted as part of this program. This would have provided a more direct validation of the results. Furthermore, the test setup did not consider the influence of fatigue loading, which is a critical design consideration for bridges and other dynamically loaded structures [28]. The study also did not investigate the performance of the connectors within a full-scale composite beam under flexural loading, which would be the ultimate test of their in-situ behavior. These limitations, while important, serve as clear directions for future research.

4.5. Theoretical and Numerical Modeling

The experimental findings from the unilateral push-out tests, particularly those from the parametric study, provide a robust dataset for the development and validation of theoretical and numerical models. While the primary focus of this study was experimental, the consistent results from the new test method lay the groundwork for a detailed computational analysis. Existing empirical models, such as the one proposed by Ollgaard et al. [31] and the Eurocode 4 design equations [15], were developed based on data from traditional two-sided tests. A key next step is to adapt and refine these models to better predict the behavior of connectors tested with the unilateral method. The slight variations in load distribution and confinement in a one-sided setup, while negligible in terms of overall capacity, could be captured by a more nuanced model [29].

Furthermore, the data from this study is ideal for calibrating and validating finite element analysis (FEA) models. A detailed FEA simulation of the unilateral push-out test specimen could be created to numerically predict the load-slip curve and failure mechanisms. Such a model would need to accurately represent the non-linear behavior of concrete, the elastoplastic response of the steel stud, and the interface behavior between the two materials [26, 40]. The experimental data on ultimate capacity and load-slip relationships for different concrete strengths and stud diameters could be used as benchmark values to ensure the accuracy of the numerical model.

The synergy between the new unilateral test and advanced numerical modeling would significantly accelerate the design and analysis process for composite structures. It would enable engineers and researchers to perform virtual experiments, exploring a much wider range of parameters—such as the effect of different loading protocols, partial shear connection, or complex geometries—without the time and cost associated with physical testing [12, 33]. This integration of experimental and computational methods represents the next logical

step in the advancement of composite construction research and design, and the unilateral test method provides the ideal foundation for this evolution.

5. CONCLUSION

In conclusion, this research successfully developed and validated a novel unilateral push-out test method for evaluating the shear performance of connectors in composite beams. The experimental results demonstrated that this simplified, one-sided setup can reliably and accurately determine the ultimate shear capacity and load-slip characteristics of headed stud shear connectors. The findings confirm that the data obtained is consistent with results from conventional two-sided push-out tests, thereby establishing the new method as a viable and effective alternative. This novel approach offers significant practical advantages, including simpler specimen fabrication, reduced material waste, and increased testing efficiency, making it a more economical and accessible tool for researchers and engineers. The study's contribution to the field is substantial, as it provides a robust and validated methodology that can streamline future experimental investigations and potentially inform updates to international design standards. The development of the unilateral push-out test is a crucial step toward optimizing the research and development of composite structures, enabling a more rapid and efficient evaluation of new materials and designs for modern construction.

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