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Flexural behavior of composite concrete deck slab-steel beams: a review

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Abstract

One of the most important structures in modern civil engineering is composite beams, which refer to beams that consist of different materials whereby the most common are concrete slabs and steel beams. This paper aims at presenting the state of research on the behavior and performance of composite beams emphasis has been put on the Shear connections. Some of the commonly used shear connectors include headed steel studs, channel connectors, and angle connectors, which improve the load bearing of steel and concrete structures. Literature review shows that important parameters such as connection type, concrete strength, and connection layout have been found to affect considerably the ultimate moment, the fatigue behavior, and the failure mode of the connection. In particular, it is important to mention that new materials, such as ultra-high performance concrete (UHPC), and connector designs offer the potential for increasing loads and durability of connections. It is within this context that this review underlines the need to identify and manage design parameters to guarantee the safe and efficient use of composites in beam structures.

Keywords: *Composite beam; Steel beam; Shear connection; UHPC; Failure mode*

1. Introduction

Composite beams are constructed using a mix of several materials, but the most popular application for these materials is in the form of concrete slabs combined with steel beams. Despite their significant differences, steel and concrete work well together. Steel is more effective under tension when used as a beam than it is when used as a slab. The concrete slab is largely Subject to compressive pressures in this instance, while the steel beam is subjected to tensile stresses, effectively exploiting the advantageous properties of each material [1]. It is typical for steel beams to support a concrete slab to be found in many structures, including bridges. A composite beam is more common in contemporary constructions where steel beams are joined to the concrete slab using different kinds of shear connections so that the two function as a single unit [2]. Shear connectors' primary function in a composite beam is to transmit longitudinal shear stresses at the steel beam-concrete slab contact in order to produce the desired composite beam behavior [3]. Composite beams employ a variety of shear connector types, including oscillating perfobond strips, waveform strips, headed studs, perfobond ribs, t-rib connectors, channel connectors, and non-welded connectors [4]. Headed stud shear connectors are the most common type of shear connectors used in steel-concrete composite construction to transfer the longitudinal shear forces at the interface between steel and concrete. The behavior of headed stud shear connectors is explored by push-out tests. According to previous researchers, the behavior of headed studs in composite construction depends on many factors, including shank diameter, height and tensile strength of studs, compressive strength and elastic modulus of concrete, direction of concrete casting, reinforcement detailing, and stud welding quality. This paper provides an overview of the most common types of steel beam-concrete slab connections.

2. Cast-in-place deck with steel beam

Cast-in-place deck slabs are a vital component of composite beam bridges, providing a structural surface that supports vehicular and pedestrian loads. These slabs are poured on-site and seamlessly integrated with supporting beams, typically made of steel or concrete, to create a unified structural system.

Hou et al., 2016 (Hou et al., 2016) Investigated the flexural behavior of composite beams with cast-in-place concrete slabs on Precast Concrete Decks (PCDs) through experimental testing of twelve specimens (see fig. 1). The specimens comprised six configurations of PCDs arranged either perpendicular or parallel to the steel beam, with concrete slab thicknesses ranging from 130 mm to 150 mm and a constant width of 800 mm. The study concluded that PPCDs are a viable alternative to traditional steel corrugated decks, offering aesthetic and cost advantages while maintaining structural integrity.

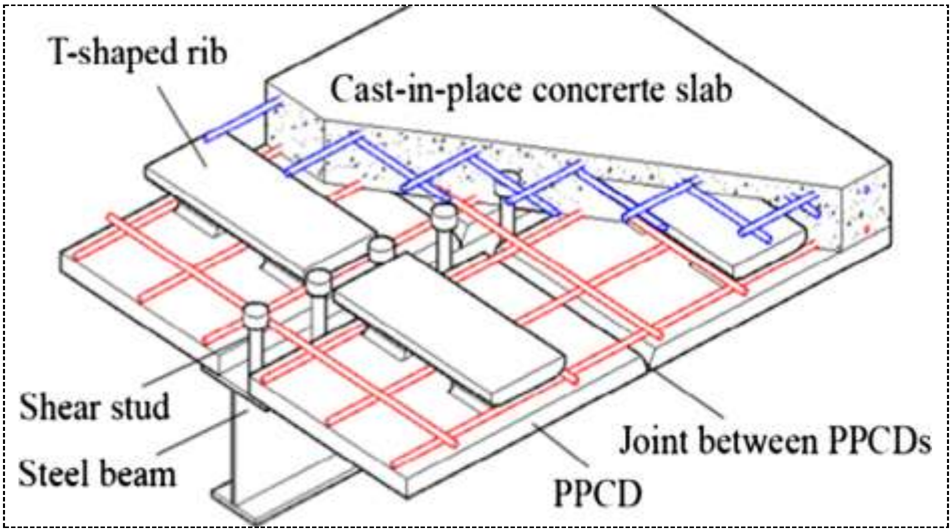

Fig. 1: Sketch of a composite beam with cast-in-place concrete slab [5].

3. Composite beam with a shear stud connection

Xue et al., 2012 [6] examine how single-stud and multi-stud shear connections behave differently when subjected to static loads. Ten push-out specimens were tested: four pairs with several studs in different configurations and one pair with a single stud measuring 22mm in diameter by 200 mm in length. There were two examples for each configuration of the multi-stud specimens, which had stud spacing of 100,150,200, and 250 mm. The findings demonstrated that the initial stiffness of single and multi-stud connections was comparable. Single-stud connections had a typical slip of around 19% more at maximum load than multi-stud configurations, although having an ultimate strength that was roughly 10% higher. No actual failure was seen in any of the specimens; instead, all failed via the yielding of the stud shanks. In multi-stud setups, studs in higher rows showed more plastic deformation than studs in lower rows.

Huh et al., 2015 [7] examined the flexural behavior of the composite beams consisting of shear stud connectors placed in shear pockets, and precast UHPC slabs were attached to steel girders. To accomplish this goal, a total of two full-scale composite beam specimens were constructed and tested. In both specimens, headed stud connections measuring 30 mm in diameter were used. With 150 mm of stud height. Six stud clusters were welded to the steel girders' upper flange in each specimen. Three studs were positioned inside a pocket measuring 150 mm by 150 mm in each cluster. The purpose of the experimental program was to assess how the stud configuration affected the behavior of the beam. The result provides recommendations for maximizing the design of composite beams that can lower construction costs by utilizing precast UHPC slab joined by big stud clusters. Tests on composite beams revealed that the stud arrangement affected the flexural stiffness and strength. Compared to studs distributed regularly, clusters that were closely spaced initially had more rigidity.

Hu et al., 2020 [8] conducted experimental testing and numerical analysis, the goal of this work was to assess the static shear behavior of large-headed stud shear connectors implanted in ultra-high performance concrete (UHPC) slabs. To study single and group stud arrangements, nine push-out specimens were tested. There were two sizes utilized for the single stud specimens: 22 mm and 30 mm. The specimen of grouped studs had six studs with a diameter of 30 mm and a 120 mm height and headed geometry. The test program assessed the impact of variables such as concrete cover thickness over the stud head, and stud spacing in the transverse direction in addition to the bigger stud diameters. The experimental findings shed light on how these bigger studs behaved when inserted into UHPC. The results contributed to the development of design equations and validation data for the numerical models created to study the behavior in more detail using parametric analysis.

Lin et al., 2016 [9] examined the static shear behavior of large-headed stud shear connectors implanted in (UHPC) slabs through numerical analysis and actual testing. To assess the behavior of both single and grouped big stud designs, nine push-out specimens were constructed. In order to construct three sets of specimens, stud diameters of 30 mm were used, which is bigger than the usual stud sizes listed in design regulations. According to the test results, specimens with big studs in UHPC slabs without any surface fractures were the only ones that had shank failure. In contrast, specimens with big studs in NSC slabs showed a combination of stud failure and splitting fractures in the concrete. Experiments showed that specimens with big studs in UHPC slabs had a shear capacity that was 10.6% greater than that of NSC slabs. The information and conclusions from this study help the use of big studs in steel-UHPC composite constructions.

Shim et al., 2001 [10] examined the design of shear connections in composite steel-concrete bridges utilizing precast decks, based on experimental push tests and a bridge model test. The specimens included studs with shank diameters of 13 mm, 16 mm, 19 mm, and 22 mm, with a height of 150 mm and a tensile strength of 450 MPa. The study found that uniform distribution of shear connectors is feasible due to their deformation capacity and load redistribution characteristics. It concluded that the stud shank area primarily influences the ultimate strength of the shear connection, and proposed empirical equations for design, emphasizing the need for careful consideration of bedding thickness and material properties to ensure structural integrity.

Lam and El-Lobody, 2005 [11] investigated the behavior of headed stud shear connectors in composite beams through experimental push-off tests and finite element modeling. Four push-off test specimens were constructed, each consisting of a steel beam (254 mm x 254 mm) connected to two concrete slabs measuring 619 mm long, 469 mm wide, and 150 mm thick, using headed shear studs with a diameter of 19 mm and a height of 100 mm. The concrete strengths varied across the tests (20, 30, 35, and 50 N/mm²). The experiments demonstrated that the ultimate shear capacity of the studs was influenced by both the concrete strength and the stud material properties, with maximum loads recorded ranging from 71.6 kN to 130.4 kN per stud.

Hanswille et al., 2017 [12] presented an experimental study on the fatigue resistance of headed shear studs used in steel-concrete composite structures, particularly focusing on their performance under cyclic loading. A total of 71 push-out tests were conducted using standard EC4 specimens, featuring a 650 mm long HEB260 steel profile connected to two 650 mm long, 600 mm wide, and 150 mm thick concrete slabs, using four-headed shear studs with a diameter of 22 mm and a height of 125 mm. The results indicated that crack initiation at the stud foot occurred at 10%–15% of the fatigue life, leading to a reduction in static strength. The study found that the static strength of the studs decreased significantly under cyclic loading, particularly affected by the peak load magnitude.

Ovuoba and Prinz, 2016 [13] investigate the fatigue capacity of headed shear studs in composite bridge girders, utilizing six double-sided push-out specimens with dimensions based on a W10x54 wide-flange section, each featuring four headed shear studs and a 6-inch concrete slab. The specimens were tested at applied stress ranges of 30 MPa to 60 MPa. The study concluded that the shear studs demonstrated higher fatigue capacities than current AASHTO limits, suggesting a need to increase the constant amplitude fatigue limit to 6.5 ksi based on the results, and emphasizing that fatigue often governs design, necessitating a re-evaluation of existing standards for shear stud connections.

Wang et al., 2019 [14] investigated the static behavior of large stud shear connectors embedded in UHPC through 18 push-out test specimens, utilizing headed studs with diameters of 22 mm and 30 mm. Specimens included both normal strength concrete (NSC) and UHPC, with dimensions of 150 mm thickness, 400 mm width, and varying heights (100 mm for UHPC and 150 mm for others). The study found that the shear strength of the 30 mm studs was approximately 19.3% higher in UHPC compared to NSC, while the shear stiffness increased by 41.8% for UHPC specimens. Conclusions indicated that larger stud diameters significantly improved shear strength and ductility, with short studs (aspect ratio of 2.3) effectively developing full strength in UHPC.

Hu et al., 2020 [15] investigate the flexural performance of large-scale steel-UHPC composite beams, specifically two specimens: a steel-NSC beam (NB) and a steel-UHPC beam (UB), both measuring 4500 mm in length and 380 mm in depth. The steel girder used had a flange size of 255 × 14 mm, with large-headed studs (ML15, 30 mm diameter) arranged in clusters within shear pockets. Each beam underwent static monotonic loading using a hydraulic actuator. The NB beam featured shear pockets filled with high-strength mortar (HSM) and UHPC, while the UB had all shear pockets filled with UHPC. The ultimate loads were 840 kN for NB and 935 kN for UB, with the latter showing improved flexural capacity and reduced interfacial slip.

Hassanin et al., 2021 [16] investigated the cyclic loading behavior of six composite beam specimens designed for evaluation, with varying degrees of shear connection (100%, 80%, and 60%). Results demonstrated that the strengthened composite beams with post-tensioning tendons showed reduced residual deflection and increased yield loads compared to non-strengthened beams, delaying failure due to cyclic loading while emphasizing the significant role of shear connection in controlling concrete flange cracking.

Nguyen et al., 2015 [17] investigate the behavior of composite beam systems at elevated temperatures. The specimens were tested under fire conditions to assess the effects of unprotected beams. Experimental findings highlight that continuity of reinforcement and the presence of interior beams significantly reduce slab deflections and enhance load-bearing capacity, with enhancement factors of 1.96 to 2.55.

4. Composite beam with channel connection

Fanaie et al., 2015 [18] presented an analytical study of composite beams using channel shear connectors arranged either face-to-face or back-to-back. The experimental work involved modeling beams with varying channel sizes, specifically, 16 channels `of 4 cm length and 8 channels of 8 cm length were tested under these conditions. The results indicated that while both arrangements performed similarly in terms of force-displacement behavior, the face-to-face configuration exhibited a slightly higher crack initiation load compared to the back-to-back arrangement. Overall, increasing channel size, number, and length enhanced the crack initiation load.

Shariati et al., 2012 [19] investigated the behavior of channel shear connectors embedded in different types of concrete slabs through a series of push-out tests. Various specimens were tested, including reinforced and unreinforced configurations, with channel connectors varying in height and length. The concrete types included high-strength, lightweight aggregate, and normal concrete. The results indicated that channel shear connectors demonstrated ductile behavior, particularly when longer connectors were used, and highlighted the importance of concrete type on overall performance.

Baran and Topkaya, 2014 [20] presented an experimental study focused on the flexural behavior of steel–concrete composite beams utilizing channel-type shear connectors. Four composite beam specimens were tested. Each composite beam comprised an IPE 240 steel section paired with a 10 cm thick concrete slab that spanned 80 cm in width. The results indicated a significant improvement in both moment capacity and service stiffness with an increase in the degree of composite action. The findings underscore the effectiveness of channel connectors in enhancing the structural performance of partially composite beams, confirming their potential as viable alternatives in composite construction.

Hosain and Pashan, 2006 [21] conducted an experimental study on channel shear connectors in composite beams, focusing on push-out tests conducted in three series (D, E, and F), each comprising twelve specimens. Each series included six specimens with solid concrete slabs and six with wide-rib profiled metal deck slabs. The channel connectors were 102 mm high, with web thicknesses of 4.7 mm and 8.2 mm, and varying lengths of 50 mm, 100 mm, and 150 mm. The concrete used had compressive strengths of 21.18 MPa for Series D, 34.80 MPa for Series E, and 28.57 MPa for Series F. The results demonstrated that the load-carrying capacity increased with channel length and depended on concrete strength, with higher strength concrete leading to channel web fractures, while lower strengths resulted in concrete crushing. Specimens with solid slabs exhibited approximately 33% higher load capacities than those with metal decks.

Giussani, 2009 [22] investigates the long-term behavior of composite steel-concrete beams subjected to temperature variations, shrinkage, and static loads. The conclusions highlight that temperature variations—particularly non-linear distributions—significantly influence stress states in the concrete slab, potentially leading to cracking. The research emphasizes the importance of accurately evaluating tensile stresses in concrete to prevent cracking, suggesting that measures like prestressing may be necessary to mitigate these effects.

5. Composite beam with angles connection

Griffin et al., 2017 [23] presented an investigation into the use of angle connectors in composite beams with precast slabs, focusing on two sets of full-size specimens: CB1, which included angle connectors, and CB2, which did not. Each specimen featured a precast slab measuring 450×60 mm and a total composite beam length of 3960 mm. The experimental work involved flexural tests to assess the strength, stiffness, and slip capacity of the connectors, with measurements taken for load-displacement behavior and crack development. Results indicated that the composite beam with angle connectors exhibited greater stiffness and comparable flexural strength to conventional beams, while also demonstrating reduced slippage. The study concludes that angle connectors can effectively replace extending rebars in precast slabs, leading to reduced construction costs and improved structural performance.

Kim, 2015 [24] presented an experimental study focused on evaluating the flexural performance of composite beams using angles as shear connectors, with seven test specimens designed to assess various parameters. The specimens included angles of sizes L-30×3, L-40×5, and L-50×6. The angle spacing varied from 200 mm to 300 mm, and some specimens utilized hollow PC slabs. Results indicated that the maximum load capacity ranged from 1,786 kN to 1,905 kN, demonstrating that composite beams exhibited increased strength, with ratios of ultimate to expected load between 1.22 and 1.55, confirming the benefits of using angles as shear connectors in enhancing flexural capacity.

Shariati et al., 2020 [25] conducted an experimental work involving eight push-out test specimens designed to investigate the monotonic behavior of C-shaped and L-shaped angle shear connectors within steel-concrete composite beams. The specimens included four C-shaped connectors and four L-shaped angle connectors, with dimensions varying by angle height (60 mm, 80 mm, 100 mm) and angle thickness (6 mm, 8 mm, 10 mm). The concrete strength ranged from approximately 22 to 31 MPa. Results showed that C-shaped connectors exhibited higher shear strength compared to L-shaped connectors, with failure modes primarily being concrete crushing-splitting and connector fracture. Notably, the L-shaped connectors tended to separate from the concrete due to a lack of flange embedment, highlighting the structural preference for C-shaped connectors in design applications.

Lee et al., 2020 [26] investigated the strength of angle-type shear connectors in concrete-filled composite beams through push-out and yield-strength tests on eight specimens. The specimens varied in height (60 mm, 80 mm, 100 mm), width (100 mm, 160 mm), and thickness (4.5 mm, 6 mm). The results indicated that increasing the height and thickness of the connectors improved both maximum strength and ductility, while the weld length had minimal impact on strength. A new design equation was proposed, emphasizing the importance of connector height, which is not considered in existing design standards, highlighting the need for revisions in design criteria for angle-type shear connectors.

Ju et al., 2014 [27] presented an experimental study on the push-out tests of welded angle shear connectors used in composite beams, involving 22 specimens designed to assess the shear capacity influenced by parameters such as angle height, welding length, and pitch. The specimens included four series: Series I utilized headed welding studs (φ19, 100mm), Series II used equal angles (L-30×30×3) with varying welding lengths (20mm, 30mm, 40mm) and pitches (200mm, 300mm), Series III employed larger angles (L-40×40×5), and Series IV featured the largest angles (L-50×50×6). The results indicated that increased welding lengths and smaller pitches significantly enhanced shear performance, with the maximum load capacities reaching up to 940 kN for the largest angle configurations, demonstrating the importance of shear connectors in improving the composite action between concrete and steel.

Alharthi et al., 2023 [28] presented an experimental work that involved testing five full-scale composite concrete-steel beams to evaluate the flexural behavior and capacity using various shear connectors, including angles. The specimens included a concrete slab with dimensions of 500 mm effective width and 80 mm thickness, connected to an IPE240 steel beam. Specifically, one specimen utilized angle shear connectors, which demonstrated improved ductility compared to those with studs or channels. The results showed that the specimen with angle connectors achieved a maximum load capacity of 471 kN and a maximum deflection of 40.14 mm, highlighting the significant role of angle connections in enhancing the overall performance of CRCSB under flexural loads.

6. Composite beam with dowel connection

Dudziński et al., 2011 [29] examined the fatigue behavior of composite beams utilizing composite dowel connections. Full-scale tests were conducted on beams with a span of 3.6 m, subjected to cyclic loads between 120 and 280 kN. The aim was to induce fatigue damage within 2 million cycles, and it was observed that one beam failed after 1.26 million cycles due to cracks propagating through the web, which ultimately led to the fracture of the lower flange. Metallographic inspections revealed that most active steel dowels exhibited fatigue cracks, emphasizing the significant role of the dowel connection in the composite beam's performance.

Lacki et al., 2021 [30] presented a parametric study of steel-concrete composite beams featuring composite dowel connectors, specifically designed for a heavily loaded warehouse ceiling with a useful load of 20 kN/m². Seven beam variants were tested, including 750×147 cross-sections, with dowel heights of 70 mm and 90 mm. The selected composite dowel beam was designed to demonstrate maximum tensile stresses of 144 MPa in the steel and compressive stresses up to -6.1 MPa in the concrete slab. The results indicated that the composite dowels, acting as continuous shear connectors, significantly reduced steel consumption while maintaining structural performance, outperforming traditional headed stud connections in load capacity and deformation resistance. The study concluded that composite dowels enhance the efficiency of composite beam designs, facilitating lighter structures without compromising safety.

Kopp et al., 2018 [31] conducted an experimental work involving a series of push-out tests designed to investigate the load-bearing behavior and failure modes of composite dowels as shear connectors in composite beams. Six series of tests were conducted. Specimens were primarily T-beams with varying dimensions: concrete slab depths of 50 mm to 180 mm, steel web thicknesses of 10 mm to 21 mm, and reinforcement ratios including Ø12 and Ø16 bars. The tests revealed that the composite dowel connections, particularly those with puzzle and clothoid shapes, demonstrated superior load-bearing capacities and sufficient deformation capacities, thus confirming their effectiveness in transferring shear forces between the steel and concrete components. The results indicated that the dowel connections are crucial for enhancing the structural integrity of composite beams, especially under static loading conditions.

Feldmann et al., 2016 [32] presented an experimental work that investigated composite dowels' performance as shear connectors in composite beams through push-out tests. Six series of tests were conducted on specimens that included T-beams with concrete slab depths ranging from 50 mm to 180 mm and steel web thicknesses of 10 mm to 21 mm. The dowels, featuring clothoid and puzzle shapes, were designed to enhance shear transfer between steel and concrete. Results indicated that these composite dowels exhibited superior load-bearing capacities compared to traditional headed studs, with significant ductility even in high-strength concrete. The findings concluded that the dowel connections are essential for improving the structural integrity of composite beams, effectively facilitating shear transfer and supporting overall stability under static loading conditions.

Seidl et al., 2013 [33] conducted an experimental work that evaluated composite dowels' performance as shear connectors in bridges through push-out tests conducted on various geometries, including fin, puzzle, and clothoidal shapes. Specimens included composite beams with steel girders measuring up to 39 m in length and reinforced concrete flanges with a thickness of 12 mm. The findings demonstrated that composite dowels effectively transmitted shear forces between the steel and concrete components, achieving high load-bearing capacities and ductile behavior under both static and cyclic loading. The study concluded that utilizing composite dowels instead of traditional shear studs enhances the structural integrity and fatigue resistance of the connections, facilitating the design of more efficient composite bridge systems.

Al-saidy et al., 2016 [34] Investigate the repair of corroded steel composite beams using carbon fiber-reinforced polymer (CFRP) plates. The experimental program aimed to assess the effectiveness of CFRP in restoring the strength and stiffness of damaged beams. Results indicated that while the elastic flexural stiffness of the damaged beams could be partially restored (up to 50%), their strength could be fully restored to the original undamaged state with CFRP application. The study concluded that CFRP plates effectively mitigate damage effects, enhancing overall beam performance.

7. Conclusion

A composite beam is more common in modern constructions where steel beams are joined to the concrete slab using different types of shear connections. This study provided an overview of the different types of shear connections used in composite beams. Based on the review, the following conclusions were drawn:

1. Composite beams, utilizing the strengths of different materials like steel and concrete, are crucial in modern civil engineering, particularly in bridge and building construction.
2. The effectiveness of composite beams heavily relies on the design and implementation of shear connections. Various connector types, such as headed steel studs, channel connectors, and angle connectors, significantly influence these structures' overall performance and safety.
3. The use of advanced materials, such as ultra-high performance concrete (UHPC), shows promise in enhancing the load-bearing capacity and durability of composite connections, potentially leading to safer and more efficient designs.
4. The study emphasizes the necessity of identifying and managing key design parameters, including connection type, concrete strength, and layout, to optimize the behavior of composite beams under various loading conditions.
5. Despite significant advancements, there remain gaps in understanding the long-term behavior of composite connections under fatigue and cyclic loading, necessitating further research to inform better design practices.
6. Future research should focus on developing standardized design equations and guidelines for using innovative materials and connector types, ensuring they are integrated into engineering practices to enhance structural integrity and performance.
7. The findings underscore the potential for improved construction methods and materials that could lead to cost-effective and structurally sound solutions in composite beam applications.

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