Enhancing Structural Performance of Steel-Concrete Composite Beams: A Review

Abstract

Steel-concrete composite beams combine steel's tensile strength with concrete's compressive strength**,** offering superior structural performance. This review highlights external post-tensioning**,** which enhances load capacity by up to 106%**,** and the importance of shear connection**,** recommending 80% or higher for optimal fatigue resistance. Fatigue behavior is critical, particularly for shear connectors, where failure often initiates at welded stud roots**.** Finite Element Modeling (FEM) aids in analyzing nonlinear behavior**,** validating experiments, and optimizing post-tensioning forces. Additionally, Fiber Reinforced Polymers (FRPs) improve durability and corrosion resistance**.** Future research should refine fatigue-resistant designs, optimize shear configurations**,** and integrate advanced materials for resilient composite structures**.**

1 Introduction

Steel-concrete composite beams represent a prevalent structural system in contemporary construction, offering a synergy between the high tensile strength of steel and the compressive strength of concrete. This combination often results in more efficient and economical solutions for a diverse range of building and bridge applications compared to using either material independently. The structural performance of these composite members is critical, necessitating a comprehensive understanding of their behavior under various loading scenarios, including both static and the repeated cycles of fatigue loads encountered in service. The sources provided focus on techniques aimed at enhancing the structural capabilities of composite beams, with a particular emphasis on external post-tensioning as a strengthening method and a detailed examination of the role of shear connection between the steel and concrete components. Furthermore, the response of these vital structural elements to fatigue loading is thoroughly investigated, given its significance for the long-term durability and safety of infrastructure[1–7].

Cyclic loading significantly impacts all bridge components, including structural elements and connections, by inducing fatigue-related degradation, stiffness reduction, and potential failures in critical regions. The accumulation of damage over time may lead to cracking, bolt loosening, or loss of composite action in steel-concrete members, necessitating advanced mitigation strategies. Research efforts are focused on incorporating innovative materials and techniques to enhance the fatigue resistance and resilience of bridge components, particularly the connections. One promising approach involves the integration of shape memory alloys (SMAs) in bolts [8–10], shear connectors, tendons, and other components [11] which leverage their unique superelastic and self-healing properties to counteract fatigue-induced damage. Additionally, advancements in high-performance materials, such as ultra-high-performance concrete (UHPC) and fiber-reinforced polymers (FRPs), contribute to prolonging the service life of bridge structures by improving energy dissipation and crack resistance. These emerging techniques, combined with refined analytical models, are instrumental in developing more durable and sustainable bridge systems capable of withstanding prolonged cyclic loading conditions.

Strengthening with External Post-Tensioning External post-tensioning has emerged as a highly effective and widely adopted technique for the strengthening and rehabilitation of steel-concrete composite beams. Research has consistently shown that the application of high-strength external tendons leads to a significant increase in the ultimate moment capacity of these structures. In one study, the use of externally post-tensioned tendons in the positive moment region increased the ultimate capacity by approximately 106%. This strengthening method not only boosts the load-carrying capacity but also improves the overall structural behavior by reducing deflection and increasing stiffness. The introduction of internal stresses through post-tensioning serves to enlarge the range of elastic behavior before yielding occurs in the steel components, allowing the structure to better resist moments generated by external loads [6,12,13].

The effectiveness of external post-tensioning is influenced by the profile of the tendons. Studies have explored various configurations, including straight, triangle, and trapezoidal profiles comparisons have indicated that trapezoidal tendon profiles can lead to an enhancement in the overall behavior of the beam compared to straight tendons. Additionally, draped tendon profiles have been reported to perform more efficiently in terms of both load capacity and deflection control, although straight tendon profiles might be preferred in some cases due to their lower cost and simpler implementation. Adding post-tensioned tendons with triangle and trapezoidal profiles has been shown to significantly increase the yield load and the ultimate load by as much as 99.1% and 105.5%, respectively. The application of the initial post-tensioning force often results in an initial upward camber of the beam, which can counteract the effects of subsequent loading. Typical initial post-tensioning forces in experimental studies have been around 81.7 kN per tendon or 107.2 kN per tendon, resulting in initial camber deflections of approximately 2.2 mm to 2.4 mm at the mid-span [5,14,15].

2 Effect of Shear Connection

The degree of shear connection between the steel beam and the concrete slab is a fundamental aspect governing the structural interaction and overall performance of composite beams. Full shear connection ensures that the steel and concrete act as a single composite unit, maximizing the beam's strength and stiffness. However, partial shear connection can offer economic advantages by reducing the number of shear connectors (typically headed studs) required. Research has extensively investigated the effects of varying the degree of shear connection, typically ranging from 40% to over 100% (achieved by adjusting the number of shear connectors). Generally, increasing the degree of shear connection enhances the ultimate load capacity and improves the deflection response of composite beams, particularly continuous ones. Conversely, at lower levels of shear connection (e.g., 40%, 60%, and 80%), a reduction in strength and stiffness has been observed compared to cases with no post-tensioning. However, the decrease in stiffness might not be as significant as the reduction in ultimate moment. Studies have also explored the re-arrangement and distribution of shear studs along the beam length to optimize performance and fatigue resistance. External post-tensioning can contribute to achieving partial continuity even in initially simple composite beams. Current recommendations suggest that for optimum performance, especially under fatigue loading, a degree of shear connection of 80% or more should be aimed for [3,16–20].

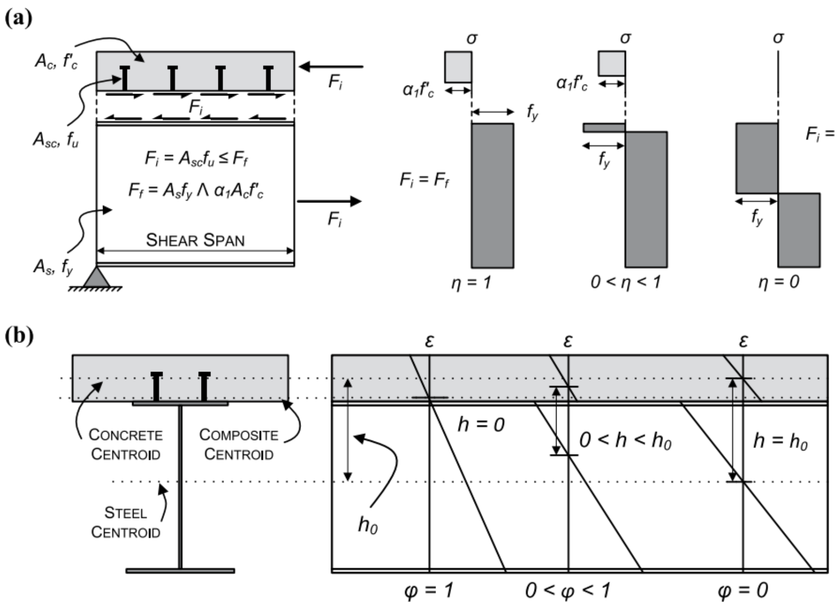

Figure 1. Degrees of (a) shear connection and (b) composite interaction [21]

3 Fatigue Behavior

Steel-concrete composite beams in bridge structures and industrial facilities are frequently subjected to repeated cyclic loads, making the understanding of their fatigue behavior paramount for ensuring long-term structural integrity and safety. Fatigue failure in these composite systems can arise from various mechanisms, including damage to the shear connectors (studs), crushing of the concrete slab, and fatigue cracking in the steel beam components. Research has particularly focused on the fatigue life of shear studs, with the most common failure mode being the initiation of damage in the welding zone at the stud root, which can then propagate to the top flange of the steel section. The amplitude of shear stress experienced by the connectors is a critical factor influencing their fatigue life. Empirical studies have led to the development of logarithmic functions that relate the shear stress amplitude to the number of loading cycles a stud can withstand before failure. The Eurocode has adopted such an expression. Investigations have also examined the growth of cumulative slippage at the steel-concrete interface under cyclic loading [22–24]. Push-out tests are commonly used to study the fatigue behavior of shear connectors, but these tests have limitations in fully replicating the complex behavior of connectors within a composite beam under flexure and cyclic loads. Cyclic loading experiments on full-scale composite beams have employed both displacement-controlled and load-controlled procedures to simulate service conditions [3,20,25–28]. The application of external post-tensioning has been shown to relieve part of the cyclic strain in the shear connectors of strengthened specimens, potentially increasing their fatigue life compared to non-post-tensioned beams. Optimizing the pitch and distribution of shear studs along the beam span is also crucial for managing fatigue demands and improving overall fatigue resistance.

Figure 2. Fatigue fracture failure of composite beam [29]

4 Finite Element Modeling (FEM)

Three-dimensional nonlinear finite element analysis has become an indispensable tool for investigating the intricate behavior of steel-concrete composite beams under various loading and strengthening configurations. Software packages like ANSYS are frequently employed to create detailed numerical models that can account for material nonlinearities, contact interactions between steel and concrete, and the effects of external post-tensioning [30,31]. A crucial step in using FEM is the validation of the model against experimental results to ensure its accuracy in predicting key response parameters such as load-deflection behavior, strain distributions, and failure modes. These models typically incorporate nonlinear material models for concrete (capable of cracking and crushing), steel (exhibiting yielding and strain hardening), and the post-tensioning tendons. Shear connectors are often modeled using discrete elements with nonlinear force-slip relationships to capture their behavior under load. Solution procedures based on methods like the variable or tangent stiffness method are used to handle material nonlinearity and achieve convergence in the numerical solutions. Prior to conducting parametric studies, a mesh sensitivity analysis is often performed to determine an appropriate element size that provides accurate results without excessive computational cost [4,32–34].

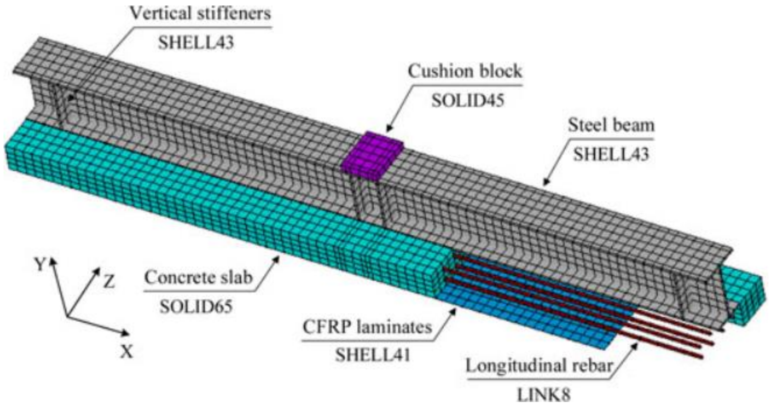

Figure 3. Establishment of the finite element model [35]

5 Fiber Reinforced Polymers (FRPs)

In addition to steel tendons, Fiber Reinforced Polymers (FRPs) such as Carbon Fiber Reinforced Polymer (CFRP), Aramid Fiber Reinforced Polymer (AFRP), and Glass Fiber Reinforced Polymer (GFRP) are also utilized for strengthening and pre-stressing concrete structures, including composite beams. FRPs offer several advantages, including high tensile strength, light weight, and resistance to corrosion, which is particularly beneficial in aggressive environments. The mechanical properties of different FRP tendons vary, with CFRP generally exhibiting superior long-term residual strength and fatigue resistance compared to steel. FRP reinforcing rods are typically manufactured using a process called pultrusion [36]. Ensuring a strong bond with concrete often involves surface treatments like spiral wraps or sand coating. Factors such as relaxation, creep, and long-term tensile strength are important considerations when using FRPs in prestressed applications. Design guidelines, such as those provided by ACI 440.4R-04, address transfer and development lengths for FRP tendons, which are influenced by factors like tensile strength, modulus of elasticity, surface preparation, and concrete strength [37,38].

6 Other Relevant Aspects

While the primary focus is on post-tensioning with tendons and shear connection using studs, other connection mechanisms, such as bolted composite joints, are also relevant in structural engineering. Studies on bolted joints in composite materials highlight factors like joint geometry, material properties, bolt tightening torque, and potential failure modes such as bearing failure and delamination. Furthermore, research has specifically addressed the effects of uniform load on externally post-tensioned composite beams under varying degrees of shear connection, analyzing the resulting moment-deflection responses and failure characteristics. To enhance the efficiency of analysis, efficient beam element models have been developed for simulating the behavior of composite beams with partial interaction, often incorporating nonlinear material models and discrete shear connector representations[39–41].

7 Conclusion

This review underscores the significant benefits of external post-tensioning as a robust technique for enhancing the strength, stiffness, and overall structural performance of steel-concrete composite beams. The degree of shear connection is identified as a critical parameter influencing load capacity, deflection characteristics, and fatigue resistance. Finite element modeling provides a powerful and increasingly refined approach for analyzing the complex nonlinear behavior of these composite systems, provided that models are rigorously validated against experimental data. Understanding the nuances of fatigue behavior, particularly in the shear connectors, remains crucial for ensuring the long-term durability and serviceability of composite beam structures subjected to repeated loading. Ongoing research continues to explore and optimize design strategies and strengthening techniques for composite beams under diverse operational conditions, including the effective use of both steel and FRP post-tensioning systems and the consideration of various loading types and connection details.

8 References

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