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(Review)

Enhancing Composite Steel-Concrete Beams: A Review of Strengthening Techniques, Performance, and Practical Applications

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ABSTRACT

This paper reviews structural behavior, load resistance, and various strengthening techniques for composite steel-concrete beams. Composite beams, which combine steel and concrete to exploit the strengths of both materials, are integral to modern construction due to their efficiency and load-bearing capabilities. However, the need for strengthening these beams arises from factors such as increased service loads, material deterioration, and changes in design codes. This review discusses the primary methods of strengthening—steel plate strengthening, fiber-reinforced polymer (FRP) applications, and external post-tensioning—detailing their effectiveness, durability, and practical implementation challenges. Each method offers specific benefits and limitations, affecting their suitability based on structural demands and economic considerations. The paper concludes with a discussion on the combined use of these techniques to enhance both the flexural and interface capacities of composite beams, emphasizing the balance between serviceability and ultimate strength improvements. The comparative analysis aims to guide the selection of the most appropriate strengthening strategy, considering the evolving landscape of construction materials and methods aimed at prolonging the lifespan and functionality of composite steel-concrete structures.

Keywords: Composite Beams, Shear Connectors, Fatigue Loading, Strengthening Techniques, Flexural Capacity

1-Introduction

Composite steel–concrete beams consist of a steel beam (usually an I-section or girder) and a concrete slab that work together as a single unit. The two materials are bonded by shear connectors (like welded studs) to prevent slip at the interface. This composite action allows the concrete slab to carry compression and the steel beam to carry tension, achieving greater stiffness and strength than either material alone. Composite beams are widely used in building floors and bridge decks due to their high strength-to-weight ratio and efficient use of materials. In practice, the concrete slab also restrains the steel beam laterally, reducing the risk of lateral–torsional buckling of the steel section.

However, existing composite beams may require strengthening for several reasons: increased service loads (e.g. heavier traffic or new usage of a building), deterioration of materials (corrosion of steel or cracking of concrete), or updated design codes demanding higher load capacity. Retrofitting such beams is often more sustainable and cost-effective than replacing them. Strengthening a composite beam is challenging because any intervention must account for the different behaviors of steel and concrete and the presence of existing loads. Engineers must ensure stability during retrofit (often propping the beam to relieve load) and choose methods that minimize disruption. This literature review discusses: (1) the structural behavior of composite steel–concrete beams under various loading conditions, (2) their load resistance and common failure mechanisms, (3) different strengthening techniques (material modifications, external reinforcements, and other retrofitting methods), (4) a comparative analysis of these strengthening methods in terms of effectiveness, durability, and practicality, and (5) case studies and recent experimental findings illustrating these concepts.

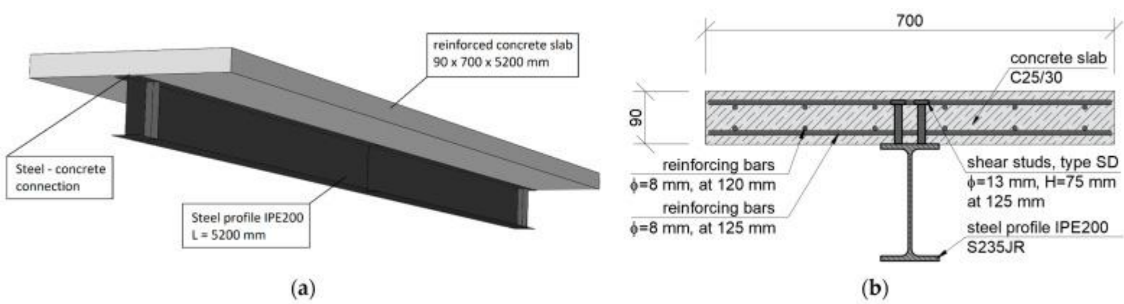

Figure 1. (a)Steel–concrete composite beam with a concrete slab on a steel I-beam, connected by shear studs and (b) cross-section detailing materials and shear connectors.

2 -Structural Behavior Under Various Loads

2.1 Monotonic (Static) Loading

In a composite beam under gradual static loading, the steel and concrete act together until interface slipping occurs. Under positive bending (sagging), the concrete slab is in compression and the steel beam's bottom flange is in tension – an ideal combination since concrete has high compressive strength and steel has high tensile capacity. If the shear connection is sufficient (full composite action), the two materials develop a single neutral axis and the beam achieves its maximum stiffness and strength. If the shear connectors are sparse or weak (partial composite action), slip can occur at the interface, leading to two distinct neutral axes in the steel and concrete components. In such partially composite beams, the slab and beam do not fully act in unison – both the concrete slab soffit and the steel top flange may experience tension due to slip, even at relatively low loads. This reduces stiffness and load capacity compared to a fully composite beam. The load–deflection response of a composite beam typically shows an initial linear elastic range, followed by yielding of the steel as the load increases. If full interaction is present, the steel yields first (providing ductility), and the concrete may crush in compression at ultimate load if the beam is loaded to failure. If interaction is partial, the connectors may start to yield or slip before the steel fully yields, altering the load distribution. The presence of the concrete slab also increases the beam's overall flexural rigidity and can significantly decrease deflections under service loads, improving performance and comfort (for example, reducing floor vibrations in buildings). Additionally, as noted, a properly connected concrete slab provides lateral restraint to the steel flange, which can prevent lateral–torsional buckling of the steel beam even at high load. This restraint is one reason composite beams can achieve better stability and higher bending resistance than equivalent steel-only beams.

In continuous composite beams (with multiple spans or fixed ends), negative bending (hogging) occurs over intermediate supports, putting the top of the steel beam in compression and the slab in tension. In negative moment regions, the concrete slab may crack since it carries tension, and the steel beam (top flange) carries compression. If the slab has reinforcing steel, it can resist some tension; otherwise, composite action in negative bending relies on any reinforcement or on external strengthening (since cracked concrete has negligible tension capacity). As a result, many composite beams are critical in negative moment regions, where loss of composite action can occur after slab cracking. Research has shown that adding external reinforcement (like fiber composites) to the slab's top or tension face can enhance negative moment capacity and control cracking. A point discussed later under strengthening techniques [1], [2], [3], [4], [5], [6].

2.2 Shear and Interface Behavior

Along with bending, composite beams must transfer longitudinal shear at the steel–concrete interface. Headed stud connectors are commonly welded to the steel flange and embedded in the concrete; they transfer shear and prevent the slab from slipping relative to the beam. Under high shear, these connectors may yield, or the surrounding concrete can crack. If connectors are closely spaced and strong, the beam approaches full composite action; if not, slip increases and the neutral axis separation described above occurs. The load–slip behavior is an important aspect of composite action. Push-out tests and beam tests show that a stronger shear connection (higher degree of shear connection) increases stiffness, moment capacity, and energy dissipation, whereas a weaker connection (partial interaction) leads to larger slips and changes in failure mode. In fact, as the degree of shear connection decreases, all key mechanical parameters (stiffness, strength, ductility) diminish, and failure modes shift from ductile (governed by steel yield) to more brittle modes (such as sudden connector failure) [7], [8], [9], [10], [11] .

2.3 Cyclic and Fatigue Loading

Under repeated or cyclic loading (as in bridges subjected to many traffic cycles or buildings under vibrating machinery), composite beams can suffer fatigue damage, especially in the shear connectors and concrete around them. Steel–concrete composite bridges experience stress range fluctuations that accumulate damage over time. Fatigue tests have shown that as cycles progress, the stud connectors gradually cause local damage in the concrete slab (concrete around the stud's cracks and crushes), effectively reducing the stiffness of the shear connection. This leads to increased slip and residual deflections after many cycles. If a stud eventually fractures (a common fatigue failure for welded connectors), the load transfers to neighboring connectors, accelerating their damage. A key observation is that controlling longitudinal cracking in the slab (parallel to the beam, along the stud line) is crucial; stronger shear connection details delay such cracking. The overall fatigue life is therefore heavily dependent on connector design and the shear connection ratio. External post-tensioning has been found to beneficially reduce fatigue stresses – for instance, adding external prestressing cables can significantly reduce strain ranges in both steel and concrete, improving fatigue performance. If connectors do deteriorate (or corrode) over time, the beam's failure mode under cyclic loading can change. Experiments indicate that as studs weaken, the ultimate failure shifts from stud shear-off to a flexural compression failure of the slab (concrete crushing at mid-span) . In other words, an initially ductile connection failure may be supplanted by a more brittle concrete failure if the connectors are no longer effective, highlighting the complex interaction of fatigue and composite action [6], [12], [13], [14], [15], [16].

In dynamic or impact loading scenarios (such as vehicular impact on a bridge girder), composite beams benefit from the energy dissipation in the steel (through plastic deformation) and the mass and damping of the concrete slab. The presence of the slab can help absorb impact energy, though it may crack the concrete. Under seismic loading (in building frames with composite beams), the cyclic reversal of moments can crack the slab (for negative cycles) and yield the steel (for positive cycles). Seismic design of composite beams often includes sufficient shear connectors and slab reinforcement such that the composite beam can form plastic hinges with predictable behavior. Research on composite frames under earthquake loading shows that properly detailed composite beams can achieve good ductility, but the shear connectors must be capable of withstanding reversed cyclic shear without failing.

Over long durations, differential creep and shrinkage in the concrete slab can introduce internal stresses at the steel–concrete interface. Creep can cause gradual increase in deflection and redistribution of bending moments (the concrete slowly transfers more load to steel as it creeps). Shrinkage can cause the slab to contract, inducing slip or additional shear in connectors. Modern designs account for creep and shrinkage effects (often by a reduced effective modulus for concrete in long-term deflection calculations). If a composite beam is continuously supported (continuous over multiple spans), creep can also relax negative moment regions and increase positive moments over time. Overall, under service conditions, composite beams generally exhibit stable long-term behavior as long as connectors and materials remain intact, but these effects are considered in serviceability checks.

2.4 Load Resistance and Failure Mechanisms

Composite beams resist loads through a combination of steel and concrete actions. The ultimate load resistance depends on the capacity of the steel section (yielding or buckling), the concrete slab (crushing or cracking), and the shear connectors (shear or pull-out failure), as well as the interaction among these components. Several failure mechanisms are observed in composite steel–concrete beams:

2.4.1 Flexural (Bending) Failure

This is a common ductile failure mode for a well-detailed composite beam. In a simply supported composite beam under sagging bending, as load increases the steel beam's bottom flange yields in tension and the concrete slab in the top compressive zone may eventually crush in compression. The sequence is typically steel yielded followed by concrete crushing if the beam is loaded to extreme levels. Steel yielding provides a warning (deflections increase significantly) and allows some redistribution of load. If shear connectors are sufficient (full interaction), the ultimate moment capacity can often reach the plastic moment of the composite section, which is higher than that of the steel beam alone due to the concrete's contribution. For example, one study noted that an unstrengthened composite beam's ultimate moment was approximately equal to the plastic moment of the steel section alone, whereas adding reinforcement (external tendons) enabled the beam to exceed the steel section's plastic moment by about 3–11%. This indicates that full composite action had engaged most of the steel's capacity, and further gains required external augmentation [17], [18], [19], [20], [21].

If the shear connectors are a weak link, the beam may fail when the connectors shear off or the concrete around them fails, causing a sudden slip between steel and concrete. This can be a brittle failure mode, as the composite action is abruptly lost. In beams with partial shear connection, the ultimate capacity might be governed by the connector strength rather than the plastic capacity of steel or concrete. For instance, tests on beams with varying connector ratios show that at lower degrees of shear connection, the ultimate failure tends to be stud fracture (or stud shear) rather than steel yielding. Connector failure typically results in a drop in load capacity because once the interface slips, the slab can no longer carry compressive force, and the steel section alone may be insufficient. In some cases, a progressive failure can happen: one connector fails, increasing load on the remaining connectors, leading to a chain reaction. To ensure ductility, design codes (e.g., Eurocode 4, AASHTO) often require a certain minimum degree of shear connection so that the beam will fail by steel yielding or concrete crushing rather than connector fracture. In retrofitting scenarios, adding shear connectors can convert a potential connector failure mode into a ductile flexural failure mode by providing full composite action [9], [10], [22], [23], [24].

Figure 2. Typical Shear Connectors

2.4.2 Concrete Slab Failure

The concrete slab can fail in several ways. Under high compressive force (in positive bending regions), the slab concrete can crush or buckle (if very thick and unreinforced, buckling of the compression zone could occur, but typically slabs are reinforced and confined). In negative bending regions, the slab usually fails by cracking in tension. If the slab has insufficient reinforcement, wide cracks can form and the slab essentially ceases to carry tension, transferring all tension to the steel beam (which might lead to steel yielding earlier in those regions). Another failure related to the slab is longitudinal shear or splitting: the concrete slab can split along the line of connectors if the horizontal shear demand exceeds the slab's internal cohesion. This is sometimes observed as a separation (delamination) of a thin layer of concrete above the steel flange when stud anchors pry it off under extreme shear. Adequate transverse reinforcement in the slab (e.g. rebar ties or mesh) is important to prevent such premature slab shear failures. In composite beams with large web openings (for services), additional failure modes like Vierendeel bending around the opening or local slab shear near the opening can occur, but these are special cases. Generally, a well-reinforced slab will not be the first component to fail; it will either crack (which is serviceability issue) or crush after the steel yields [9], [10], [22], [23], [24], [25], [26].

The steel section can fail by yielding (plastic hinge formation) or by instability. Yielding is ductile and often desired as the governing failure as it provides rotation capacity. If the steel beam is laterally unbraced (which is uncommon in composite construction because the slab braces it), lateral–torsional buckling (LTB) can occur at a lower load than yielding. In composite beams, LTB is mitigated because the slab (when properly connected) acts like continuous lateral bracing for the top flange. Nonetheless, if the shear connection is very flexible, the slab might not fully restrain the beam, and a form of buckling can occur. Local buckling of the steel flange or web is another possibility, especially if the steel section is slender. Under high compressive stress (in the top flange at mid-span or bottom flange in negative moment zones), flange local buckling can precede overall failure. This is usually addressed in design by using compact steel sections that can develop plastic stress without local buckling. When strengthening beams by adding plates, one must also consider buckling of the new composite steel section (e.g., a welded cover plate can change the plate buckling behavior). Studies have noted that simply increasing cross-sectional area may not fully restore capacity if stability issues govern; reducing the buckling length (through bracing) or preventing local buckling may be necessary in conjunction. In summary, steel failure modes can be ductile (yielding) or brittle (buckling) depending on bracing and slenderness [6], [12], [13], [14], [27], [28], [29], [30], [31], [32].

Over the long term, repeated loading can cause a type of failure distinct from the monotonic cases. Fatigue failure of welded shear studs is a known concern – a crack can initiate at the weld or in the stud shank and grow under cyclic loading, eventually causing the stud to break. Fatigue can also occur in reinforcing bars (if stress ranges are high) or even in the steel beam (at details like welds or holes). Generally, the steel I-beam itself, if free of stress concentrations, has a high fatigue life under usual stress ranges; studs are often the critical fatigue detail. As noted earlier, stud fatigue and potential corrosion can lead to a gradual change in behavior – initially the beam may be fully composite, but if some studs crack over time, the beam transitions toward partial composite action, with increasing deflections and eventually a lower ultimate strength (possibly governed by a different mechanism like concrete crushing once enough studs are lost) . Design codes often require fatigue checks for composite bridges, ensuring the shear connectors and other details have adequate life.

In design practice, engineers aim for a ductile flexural failure (steel yielding) as the governing failure mode for composite beams. This is achieved by providing sufficient shear connection and slab reinforcement so that the steel yields before connectors or concrete fail. When strengthening existing beams, it’s important to similarly ensure that the chosen method does not introduce a brittle failure. For instance, bonding a very strong material (like CFRP) to a beam could raise the yield moment above the level at which the concrete slab would crush or the connectors would fail – so the retrofit must be designed holistically to avoid shifting the failure to an undesirable mode. Testing and analyses are used to verify that after strengthening, the beam can still achieve a ductile failure or at least has adequate warning before collapse [33], [34], [35], [36].

2.5 Strengthening Techniques for Composite Beams

Various techniques have been developed to strengthen composite steel–concrete beams, broadly categorized as: (1) material modifications to the existing components, (2) external reinforcement additions, and (3) other retrofitting methods. Often, a combination of methods is used to address both steel and concrete parts of the beam. The choice of technique depends on the deficiency to be addressed (e.g. insufficient flexural capacity, shear connector issues, excessive deflection) and practical constraints (access, cost, downtime). Below, we review these techniques and their implementation. Material modification methods involve altering or enhancing the materials within the composite section to improve capacity. This typically means increasing the cross-sectional area or using higher-strength materials in the slab or beam.

2.5.1 Concrete Overlay or Infill

One way to strengthen a composite beam is to increase the concrete slab thickness or add a new layer of concrete over the existing slab (often using high-performance concrete). By casting a thicker slab (and ensuring it is composite with the steel via new connectors or bonding), the compressive force the slab can carry is increased, thus raising the beam's flexural capacity and stiffness. Modern retrofits may use ultra-high-performance concrete (UHPC) or fiber-reinforced concrete as a thin overlay on the slab. UHPC overlays can provide extremely high compressive strength and durability in a relatively small thickness. Experimental studies on "hybrid" concrete beams (normal concrete plus a UHPC layer) have shown significant gains in moment capacity. For instance, doubling a UHPC layer from 25 mm to 50 mm was found to increase flexural capacity by about 28–35% for certain span-to-depth ratios, and even up to ~70% in beams with higher slenderness ratios. While that study was on a concrete beam strengthened with UHPC, it indicates the potential magnitude of improvement. In a composite steel–concrete bridge deck, adding a 50–75 mm UHPC overlay (properly bonded and anchored) can substantially increase capacity and protect the slab from environmental damage. Key considerations for overlays include the interface bond (often shear connectors or surface roughening are needed between old and new concrete) and added weight. Designers must ensure the existing structure can support the additional dead load of the new concrete, though UHPC can be used in thinner sections to mitigate weight [37], [38]. A recent strengthening approach related to this is to encase part of the steel section in concrete – for example, encasing a corroded steel girder bottom flange in a high-strength grout or concrete jacket. This not only restores lost section but can also improve shear connection if the encasement is tied into the slab. Such approaches blur into the territory of combined material/external techniques.

2.5.2 Improving Concrete Properties

If the concrete slab is of poor quality or cracked, one might inject cracks with epoxy to restore monolithic behavior (repair) or add fiber-reinforced polymer rods in saw-cut grooves (near-surface mounted reinforcement) to effectively add reinforcement to the slab. While these count as external additions (FRP bars), they are internal to the slab, so arguably a material modification. Using fiber-reinforced concrete (FRC) for repairs or overlays can improve the slab's post-cracking behavior. For example, adding a layer of FRC or textile-reinforced concrete on the tension face of a slab (the bottom if negative moment region) increases its tensile resistance and crack control, thereby enhancing composite action under negative moments [39], [40], [41], [42], [43], [44], [45], [46], [47], [48].

2.5.3 Shear Connector Upgrades

Although this might be considered a separate retrofitting method, it also involves adding material (new connectors) between steel and concrete. Replacing or augmenting existing shear connectors with higher-strength or larger connectors can increase the degree of composite action. There are proprietary high-strength friction-grip bolts or post-installed anchors that serve as shear connectors in old composite beams. These typically require drilling through the slab and flange, inserting a bolt or anchor with epoxy grout, and thus "materially" modifying the interface to be stronger. Pathirana et al. (2015) demonstrated a method of coring holes in the slab and installing new bolted shear connectors with grout to retrofit non-composite beams. By doing so, previously separate steel and concrete elements become a composite section, dramatically increasing stiffness and strength (in their tests, retrofitted beams achieved full composite flexural capacity comparable to originally composite beams) [49]. We will discuss this further under retrofitting, but it is fundamentally adding high-strength material (connectors and grout) to the composite interface.

In summary, material modification techniques aim to utilize better or more material in the existing cross-section. Increasing the cross-sectional area (either steel or concrete) directly boosts the load-carrying capacity. However, one must ensure compatibility between old and new materials (proper bonding of new concrete, welding procedures for new steel plates, etc.) and avoid adverse effects like shrinkage stress or added weight without sufficient benefit. Often, material modifications are used in conjunction with external reinforcements – for example, adding a concrete overlay and some external steel or FRP reinforcement to the tension zone.

2.5.4 External Reinforcement Additions

External reinforcement techniques involve attaching additional structural elements to the existing beam to increase strength or stiffness. These do not fundamentally change the original materials but add new load-carrying components externally. Common external strengthening methods include:

A traditional method (since the 20th century) to strengthen steel beams (and thus composite beams) is to attach steel cover plates to the beam's flanges or web. For a composite beam, the most effective location is usually the tension flange (bottom flange in positive moment regions) – a steel plate can be welded or bolted to it, increasing the flange area and the section modulus. This method directly enhances flexural capacity. Bolting plates is an alternative to welding, avoiding some issues by using high-strength bolts to clamp the new plate to the existing steel. To develop composite action between the old beam and new plate, preloaded (friction grip) bolts are often used so that slip is minimized. Bolted plates tend to be thicker to accommodate bolt holes and development lengths. A variant is to bolt a channel or tee-section to the beam as reinforcement (effectively like adding a second beam either below or beside the original). This was noted in practice – bolting on new steel sections is common for strengthening existing steel work. The effectiveness of steel plate bonding is high: a plate can be sized to restore or exceed the original moment capacity. For example, welding a 10–20 mm thick plate along the tension flange can raise the yield moment substantially (one study optimized plate thickness between 6–22 mm and found an optimal point beyond which extra thickness yields diminishing returns). Contemporary research, such as Szewczyk & Szumigała (2021), used numerical optimization to choose a plate size that maximizes capacity gain relative to cost. They validated that adding a plate increases the beam's plastic moment and stiffness, but beyond a certain thickness, the additional benefit is small compared to the added weight and cost [50]. Thus, an "optimum" plate size can be determined. Plate bonding addresses flexural strength, but if the beam is slender, it may also require additional stiffeners or bracing to realize the full advantage (since adding a plate makes the compression flange stronger, one must ensure the compression flange doesn't buckle first).

2.5.5 Fiber-Reinforced Polymer (FRP) Laminate Bonding:

In the last few decades, externally bonded FRP has emerged as a popular strengthening method for both concrete and steel structures. For composite beams, the typical approach is to bond carbon fiber–reinforced polymer (CFRP) laminates or sheets to the tension side of the beam. This could mean bonding CFRP plates to the underside of the steel beam's bottom flange, or, in negative moment regions, bonding CFRP to the underside of the concrete slab (which acts as the tension face when the beam is upside-down in testing or under negative bending) . CFRP materials have extremely high tensile strength-to-weight ratios and do not corrode, making them attractive for strengthening. They are adhered with structural epoxy. Numerous experiments have shown CFRP bonding can increase the flexural capacity of steel beams significantly. For instance, a review by Mishra (2022) reported that a single-layer CFRP plate bonded to a steel–concrete beam increased its load capacity by about 18%, and a double-layer provided 22% improvement. These gains are moderate, but multiple layers are often limited by premature de-bonding of the FRP or by the need for anchors, so 1–2 layers are common. One key advantage of CFRP is the lightweight, thin profile – it adds negligible weight and depth to the beam, preserving clearance and not requiring heavy installation equipment. However, direct bonding of CFRP to steel can be challenging: the steel surface must be thoroughly prepared (sandblasted), and the bond may be sensitive to creep and fatigue (steel's elastic nature means under repeated loading the adhesive layer sees cyclic shear). To mitigate de-bonding, some retrofits use mechanical anchors or U-wraps at the plate ends. Research by Wan et al. (2019) and others has taken CFRP strengthening further by prestressing the CFRP plates before bonding. Prestressed CFRP means the laminate is tensioned (e.g., using hydraulic jacks) and anchored to the beam, so that it is active even at service loads and the beam behaves as if it had an external pre-stressing force. This technique can recuperate deflection (camber the beam upward) and use more of the CFRP's high strength (since CFRP often would not reach full capacity if the steel yields first in non-prestressed applications). Prestressed CFRP has shown larger gains: one case study strengthened a 16 m old bridge beam with prestressed CFRP plates and achieved a higher cracking load and ultimate load, effectively changing the beam's failure mode from under-reinforced (steel yielding) to over-reinforced (concrete crushing) due to the added tensile force.

Another study indicated that externally bonded CFRP plates with post-tensioning could raise a composite beam’s capacity by 37–60%, depending on tendon profile (straight vs draped). FRP reinforcement can also be applied in shear (e.g., wrapping beams or around connectors), but for composite beams the focus is usually flexural. It’s worth noting that CFRP, while very strong, is linear elastic to failure and relatively brittle – when it fails (by rupture or debonding), it doesn’t yield like steel. So retrofits with FRP are often designed such that the steel will yield to provide ductility and the FRP will take the excess load until near failure. Glass FRP (GFRP) or other fibers have also been studied, but CFRP with high modulus is preferred for stiffening beams. Overall, FRP bonding has become a go-to method for moderate strengthening needs because it is easy to install with minimal downtime and does not require heavy modification of the structure [6], [13], [51], [52], [53] .

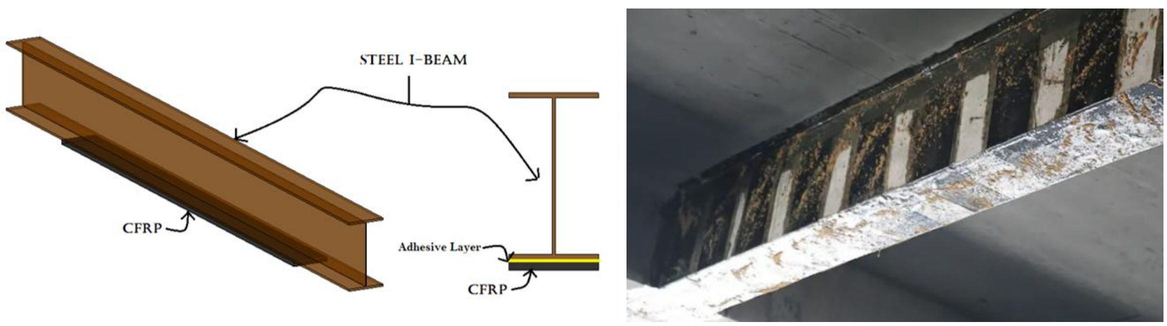

Figure 3. Steel I-beam strengthened with a CFRP plate bonded to its bottom flange (yellow layer is adhesive).

2.5.6 External Post-Tensioning (Tendons or Bars)

Another highly effective technique is to apply external post-tensioning to the composite beam. This involves installing high-strength steel cables or rods alongside or beneath the beam and anchoring them at the ends, then tensioning them to induce an uplifting force (counteracting part of the beam’s loading). External post-tensioning has been widely used in bridge rehabilitation. For example, Iowa DOT in the early 2000s strengthened a continuous composite bridge by adding post-tensioned CFRP rods under the girders in positive moment regions. The effect of external tendons is to reduce the beam’s net stress under service loads (by imposing a moment opposite to deflection) and to increase yielding and ultimate loads by essentially adding a force couple. Chen et al. (2009) tested composite beams with external steel tendons and found 49% increase in yield load and 53% in ultimate load with straight tendons [54] . Draped tendons (curved profile) can also be used to optimize the moment diagram, achieving even higher capacity gains (one study reported 60% increase with a parabolic CFRP tendon profile) . The components of an external PT system include anchorages at the beam ends (often clamped to the beam's web or flange), deviators if a draped profile is used, and the tensioned cable itself. In composite beams, the tendon is usually placed near the bottom of the steel beam so as to produce an upward bending effect. An innovative approach combined CFRP and post-tensioning: using CFRP plates as tendons. One case showed that using three parallel CFRP strips post-tensioned under a beam successfully increased stiffness and capacity, with anchors bolted to the beam's ends (see Figure 4 for the pre-stressing setup) . External post-tensioning is advantageous because it can be done while the structure is in service (sometimes traffic can continue with partial lane closures during installation), and the amount of strengthening can be tuned by adjusting the prestress force. It also inherently introduces compressive force to the concrete slab (helping to close cracks) [55]. The downsides are the need for space at the beam ends to install anchor hardware and the need to protect the tendons from corrosion or vandalism. Usually, external tendons are left unbonded (except at anchors and deviators), which means the beam and tendon interact through the anchor forces. Provided the anchors are secure, this method is very effective and has been validated on full-scale bridges. Ayyoub et al. even investigated different tendon profiles and noted that while draped profiles yield better structural efficiency, straight profiles may be preferred for simplicity and economics.

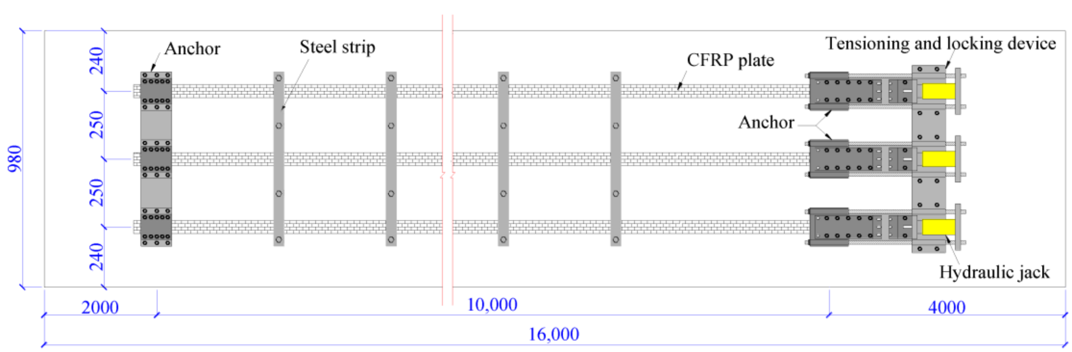

Figure 4. Schematic diagram of the prestressing of CFRP plates, Zhao et al. (2023)

Each external reinforcement method must be carefully engineered to act compositely with the existing structure. For steel plates, that means secure welding or bolting with no slip; for FRP, a reliable adhesive bond or mechanical anchorage; for tendons, stiff anchors and, often, some initial prestress to ensure engagement. A notable aspect of external reinforcements is whether the structure is strengthened under load or after unloading. Strengthening under existing load (dead load remains on the beam) is common in practice since one cannot fully unload a bridge or floor easily. If, for example, a steel plate is welded under load, the existing beam carries the pre-load, and the new plate will carry only additional load beyond that (unless the beam yields and sheds some load to the plate). There are two approaches: keep the beam in elastic range during retrofit, so the new reinforcement only takes new loads, or allow yielding so that upon strengthening, some load redistributes to the new reinforcement. The latter can be more efficient – several studies demonstrated that if a beam is strengthened after some yield (plastic redistribution), the new plate can be fully utilized for additional capacity [6], [12], [53], [56], [57] . In their experiment, they welded a plate to a composite beam while it was under sustained load, simulating real conditions. The results showed that the strengthened beam had higher stiffness and yield load, and the FE model correlated well with test results. This confirms that welded plate retrofits can be done without fully unloading the beam, although one must manage welding-induced stresses carefully. Similarly, when applying FRP or external tendons under load, one may choose to jack up (camber) the beam slightly to transfer some load off it, or just apply the reinforcement and rely on additional loading to engage it. Other studies reported the effect of different preload levels on strengthening outcome and found that higher preloads reduce the immediate effectiveness of the strengthening (since more of the new capacity is consumed by existing load), but after yielding, the ultimate capacity was similar if plastic redistribution occurs [14], [58], [59], [60] .

In summary, external reinforcements provide versatile options: steel plates are robust and increase strength substantially but are heavy and susceptible to corrosion; FRP is lightweight and easy to install but its performance can be limited by bond and it's less effective in extremely high-demand scenarios unless prestressed; external post-tensioning can achieve large strength gains and also control deflections, making it ideal for bridges, though it requires maintenance of the tensioning system. These methods can also be combined – known as hybrid strengthening.

2.6 Comparative Analysis of Strengthening Methods

The various strengthening techniques for composite steel-concrete beams, each method presents unique advantages in terms of effectiveness, durability, durability, and practicality. Steel plate strengthening can significantly increase flexural capacity by 20-50%, though it requires maintenance to manage corrosion and fatigue, and the installation process is labor-intensive. Fiber-reinforced polymer (FRP) strengthening, while typically yielding moderate capacity increases of 20-30%, offers excellent durability against corrosion and a relatively straightforward installation process, though the adhesives used can degrade under adverse conditions. External post-tensioning provides substantial improvements in strength and stiffness, around 30-60%, but involves complex installations requiring access to beam ends. Engineers often employ a combination of these methods to optimize both the structural capacity and serviceability, tailoring the approach based on whether the primary concern is serviceability or ultimate strength. The cost-effectiveness of each method varies, with FRP and shear connectors generally providing moderate improvements at lower costs, while steel plating and post-tensioning, though more costly, offer significant enhancements. This multifaceted approach to strengthening reflects an ongoing evolution in construction practices, aiming for more efficient and sustainable solutions to extend the lifespan of infrastructure.

3 – Recommendations

- **Improved Performance:** Strengthening techniques such as steel plate bonding, FRP application, and external post-tensioning significantly enhance the structural capacity and stiffness of composite beams.
- **Technique Selection:** The choice of strengthening method depends on structural requirements, environmental conditions, and accessibility for installation.
- **Durability Concerns:** Long-term durability is critical, requiring protective measures and regular maintenance to counter environmental effects.
- **Cost and Practicality:** Economic and practical considerations influence method selection, with FRP and connectors being cost-effective for moderate improvements, and steel plating and post-tensioning suitable for significant enhancements.
- **Future Research:** Ongoing research is needed to develop more efficient and sustainable strengthening solutions, focusing on hybrid techniques and innovative material

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Conflict of Interest

A declaration of conflict of interest.

4 -References

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