**Journal of Mechanical, Civil and Industrial Engineering**
ISSN: 2709-0809
DOI: 10.32996/jmcie
Journal Homepage: www.al-kindipublisher.com/index.php/jmcie

JMCIE
AL-KINDI CENTER FOR RESEARCH AND DEVELOPMENT

**| RESEARCH ARTICLE**

# Review of Experimental and FE Parametric Analysis of CFRP-Strengthened Steel-Concrete Composite Beams

**Mihir Mishra**
*Civil and environmental engineering, Texas A & M University, College Station, United States*
**Corresponding Author**: **Mihir Mishra**, E-mail: mihir92@gmail.com (M. M.)

## | ABSTRACT
Carbon-fiber-reinforced polymer (CFRP) laminates offer a promising solution to enhance the performance of continuous composite beams, particularly in hogging moment zones where tensile stresses are critical. This study extensively reviews the enhancement of flexural capacity and fracture resistance in steel-concrete composite beams (SCCB) reinforced with CFRP at the region of hogging moment. The reviewed literature focuses on experimental programs involving flexural testing in an inverted orientation under four-point loading conditions. This setup replicates the characteristics of continuous SCCBs in hogging moment zones. Experimental results were employed to validate a finite element (FE) model to simulate the nonlinear flexural behavior of both reinforced and plain beams. The literature involving FE model analysis demonstrated excellent agreement with experimental data, confirming its accuracy in predicting numerous parameters' involvement in beam performance. Findings reveal that CFRP laminates significantly enhance beam capacity, with single-layer laminates increasing capacity by 18% and double-layer laminates achieving a 22% improvement. Failure in reinforced beams typically progresses from yielding of steel rebars to rupture of CFRP laminates, followed by diagonal cracking near the supports. For optimal strengthening outcomes, CFRP application is recommended for bridges exhibiting a minimum of 80% composite behavior between the steel members and concrete components. This study highlighted the potential of CFRP laminates as an effective retrofitting technique for steel-concrete composite beams to enhance structural performance and extend service life, particularly in infrastructure subjected to high tensile demands.

## | KEYWORDS
Steel concrete composite, flexural strength, parametric analysis, carbon-fiber-reinforced polymer, FE modeling.

## ARTICLE INFORMATION
**| ACCEPTED:** 01 July 2022 **PUBLISHED:** 27 December 2022 **DOI:** 10.32996/jmcie.2022.3.3.12

## 1. Introduction
The use of eco-friendly building materials is crucial to the construction industry's transition to sustainable development. There have been a number of review papers published on the topic of increasing concrete strength using different materials and processes, as well as the benefits to the economy and environment (Ahmed & Sobuz, 2011b; Akid, Shah, et al., 2021; Rana et al., 2022) A structural component that is composite is one that uses two or more non-identical materials. Composite members made of steel and concrete are quite popular in structural engineering due to their many useful properties that make them preferable to their individual components (Ekmekyapar & Al-Eliwi, 2016). Infilled steel-concrete composite (SCC) members are thin-walled and have steel tubes filled with concrete to increase their stiffness and load-carrying capability. Reports indicate that structural steel concrete is the best material to use for long-span structural components that are subject to seismic loads and vibrations and need certain cross-sectional dimensions (Madenci et al., 2022). Merging the best features of concrete and steel, it has ideal cross-sectional dimensions, excellent strength, stability, and toughness. As a result of natural and environmental deterioration and the possibility of updating a structural element to manage higher loads, strengthening the flexural members of SCC-beam (SCCB) is necessary (Ahmed & Sobuz, 2011b; Akid, Shah, et al., 2021; Akid, Wasiew, et al., 2021; Wu et al., 2022) Recently, engineers have

strengthened steel sections using carbon fiber-reinforced polymer (CFRP) methods. These blueprints are perfect for enduring harsh weather since they have a higher strength-to-weight ratio than steel. In addition, their flexibility and strength are second to none. Earlier studies on the behavior of CFRP-confined SCCB focused on shorter lengths of CFRP (Zhu et al., 2016). However, research in this field is still in its infancy, and real-world engineering beams are often much thinner. In recent years, many analytical and experimental investigations on the behavior of short, undamaged SCCB reinforced with CFRP sheets have been conducted (Liu et al., 2022). The results demonstrated that the CFRP wrapping might enhance the load-bearing capacity and perhaps avoid local buckling of the steel tube. In the last decade, fiber-reinforced polymer (FRP) beams have become more popular in the construction sector due to their many desirable properties (Kang et al., 2021; Xu et al., 2021) The ongoing decline in the price of various fiber materials has also prompted discussions about using them in reinforced concrete instead of traditional steel. Use of FRP profiles as structural elements in beam and column applications is common (Loqman et al., 2018). First, there are the standard FRP tubes; second, there are FRP profiles; and third, there are hybrid columns that combine FRP tubes with steel and concrete. Using the strength of the FRP, the primary objective of FRP members is to limit pressure in the transverse direction. Since fiber-reinforced composite beams and columns are great for increasing strength, rigidity, and ductility, they are now the focus of most researchers' attention.

In parallel to experimentation works, numerous theoretical and computational research have been done to address the effect of web holes on the structural capacity of supported steel-concrete composite beams (Xu et al., 2021). In order to foretell the ultimate capacity of steel-concrete composite beams with rectangular web holes that are either eccentric or concentric with regard to the height of the steel beam, Fahmy (1996) provided a theoretical model. Moment capability and shear stress both rose with incremental eccentricity ratio toward the slab, according to the findings. The stiffness matrix method also gives acceptable approximations for the maximum deflection of web-opening steel-concrete composite beams (Madenci et al., 2022).

To study the structural behavior of composite beams with wide rectangular web holes, Wang and Chung (2008) developed a two-dimensional FE model with plane stress. The model for shear connections was based on distorted springs. Experiments and literature-based calculations of the shear force and bending moments acting on the composite section at failure were highly congruent. In order to investigate how different web opening shapes affect the load-deflection and ultimate capacity of composite plate girders with a horizontal curvature, the LUSAS program can also be used to create a 3D FE model. Whatever the geometry of the apertures, the results show that they lowered the ultimate shear strength of horizontally curved composite plate girders (Akid, Wasiew, et al., 2021). The FE mesh model used in their study, along with the steel-concrete composite arrangement, is shown in Fig. 1 (Mansour, 2021).

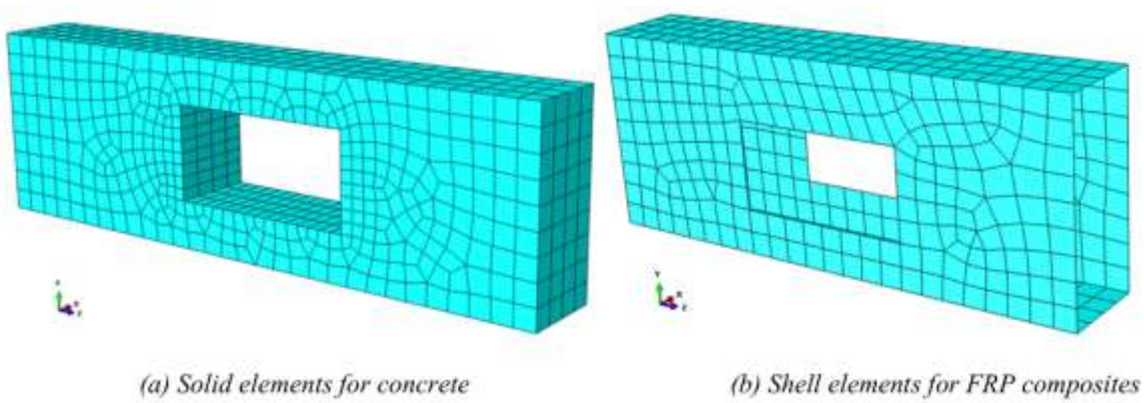



Fig. 1. Concrete, fiber-reinforced plastic, and steel reinforcement finite element model (Mansour, 2021).

Previous studies have extensively explored the use of FEM in the analysis of SCC-beams, particularly focusing on the interaction between steel, concrete, and shear connectors. Additionally, while previous work has modeled CFRP-concrete bond behavior through simplified bond-slip models, there is limited focus on the long-term durability and interface degradation of the CFRP in composite beams under varying environmental conditions (Ahmed & Sobuz, 2011a, 2011c). This study aims to perform an extensive literature study to highlight and discuss the experimental evaluation and FE modeling of SCC beams. Moreover, this paper aims to address the existing gaps in FEM simulations, particularly the inadequacies in representing non-linear material behavior and interface debonding under cyclic loading conditions. By analyzing recent advancements in multi-scale modeling, material ch aracterization, and durability testing, this study provides a comprehensive understanding of the current state of research and highlights the critical areas for future development in the FE modeling of CFRP-strengthened composite structures.

**2. Literature Review**

Early studies on the FE analysis (FEA) of SCCBs largely focused on the simulation of basic steel-concrete interaction and shear transfer mechanisms. A study by Katwal et al. (2018) provided a fundamental approach by employing beam and shell elements to model the interactions between concrete and steel members, focusing on the shear connectors and their impact on the load distribution in composite beams. Their model highlighted the importance of accurately simulating the bond-slip behavior at the interface between the concrete slab and steel beam, which significantly influenced the bending response of the beam under flexural loads.

Further advancements in FEM have integrated more complex material models and loading conditions. According to Loqman et al. (2018), the use of solid elements to model the concrete slab, combined with beam elements for the steel beam, allows for a more detailed analysis of the stress distribution and failure modes under bending. The study highlighted that incorporating plasticity models for concrete and the non-linear behavior of shear connectors provides a more accurate representation of the real-world performance of composite beams. Their findings demonstrated that under high loads, the shear failure in connectors plays a dominant role in the ultimate strength of the composite system.

Various studies have examined the integration of CFRP reinforcement in composite beams due to its potential to enhance the beam's strength-to-weight ratio, durability, and fatigue resistance. Madenci et al. (2022) investigated the effect of externally bonded CFRP plates on the flexural behavior of composite beams. The study used layered shell elements to model the CFRP and concrete slab, as well as beam elements for the steel beam. The results showed that adding CFRP significantly enhanced the flexural strength and serviceability of the beam, particularly under fatigue loading. The study concluded that CFRP reinforcement could be a cost-effective solution to extend the lifespan of steel-concrete composite beams exposed to aggressive environmental conditions.

Al-Saawani et al. (2022) explored the role of CFRP in strengthening existing steel-concrete composite beams. They employed multi-layered shell elements to simulate the CFRP layers and their interaction with the concrete slab. Their study concluded that the bonding quality between the CFRP and concrete was crucial in determining the effectiveness of the CFRP in enhancing the beam's strength. The study recommended the use of adhesive bonding techniques that improved the load-carrying capacity and prevented premature debonding under cyclic loading (Sobuz et al., 2011).

The bond-slip characteristics between CFRP and concrete are critical aspects that influence the load transfer efficiency in composite beams. Jasim et al. (2020) developed a 3D FE model that included detailed bond-slip interaction models to simulate the interface attributes between CFRP and composites. Their model revealed that the bond-slip interaction at the CFRP-concrete interface is highly sensitive to factors such as CFRP thickness, bonding adhesive properties, and environmental conditions. The study concluded that optimized bonding techniques can mitigate the risk of debonding failure and enhance the long-term integrity of the composite system. These findings align with the conclusions of Wang and Chung (2008), who observed that interfacial debonding is one of the primary failure modes in CFRP-integrated concrete elements under loading. In a study by Gotame et al. (2022), the authors used contact and target elements to model the shear transfer between the steel, concrete, and CFRP. The study emphasized that the interface stiffness between the materials is crucial in determining the failure load and the overall performance of CFRP-reinforced composite beams. The results showed that increased interface stiffness enhances the load-bearing capacity and serviceability of the composite beam.

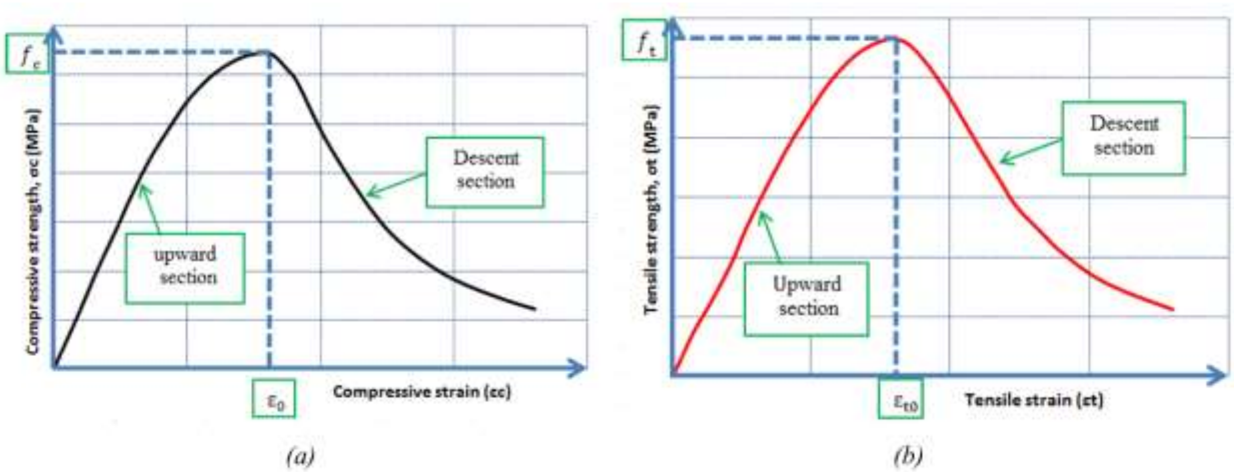



Fig. 2. Stress-strain diagram defining compression of concrete (Mansour et al., 2022).

The shear connectors in SCCBs reinforced with CFRP are pivotal in transferring the load between the concrete slab and steel beam. Several studies have focused on improving the accuracy of modeling these connectors. Pang et al. (2021) introduced a non-linear model for shear connectors that incorporated frictional resistance and slip behavior. Their FE model demonstrated that accurately representing the non-linear shear-slip behavior in connectors significantly improves the prediction of beam deflection and ultimate strength. Additionally, Kadhim et al. (2020) proposed an advanced material model for the CFRP layers, incorporating transverse shear and inelastic behavior under loading. Their study illustrated that the failure modes of CFRP-strengthened beams were governed by CFRP rupture, concrete cracking, and debonding at the interface. They concluded that FE models that account for these complex failure modes are essential for predicting the overall structural performance of CFRP-reinforced SC composite beams. Fig. 2 illustrates the typical stress-strain association of concrete using UHPFRC (Mansour et al., 2022).

**3. Experimentation of SC composite beams with CFRP**

The use of CFRP in SCCB has been extensively investigated to understand its effects on flexural behavior, stiffness, and failure mechanisms. Researchers have designed experimental programs to explore the influence of CFRP strengthening on the structural response of these beams, focusing on critical zones such as hogging moment regions where tensile stresses dominate. The following paragraphs detail the experimental setups, methodologies, and key findings from recent studies, emphasizing their practical significance.

Preparing specimens for experimental testing typically involves fabricating steel-concrete composite beams with various configurations of CFRP. The concrete slab is mechanically ground to expose aggregates as part of the surface preparation, ensuring optimal adhesion between the CFRP laminates and the substrate. Kabbo et al. examined the influence of surface roughness on the effectiveness of CFRP bonding, concluding that proper surface treatment significantly enhances the stress transfer between the materials. Epoxy resin adhesives, commonly used in CFRP applications, are applied in controlled environments to prevent air voids or imperfections, which might otherwise compromise the bond quality. Fig. 3, which shows the comparisons between the numerical findings and the test data for the baseline beam and the upgraded beam featuring a single layer, respectively, are based on the work of Mansour et al. (2022).

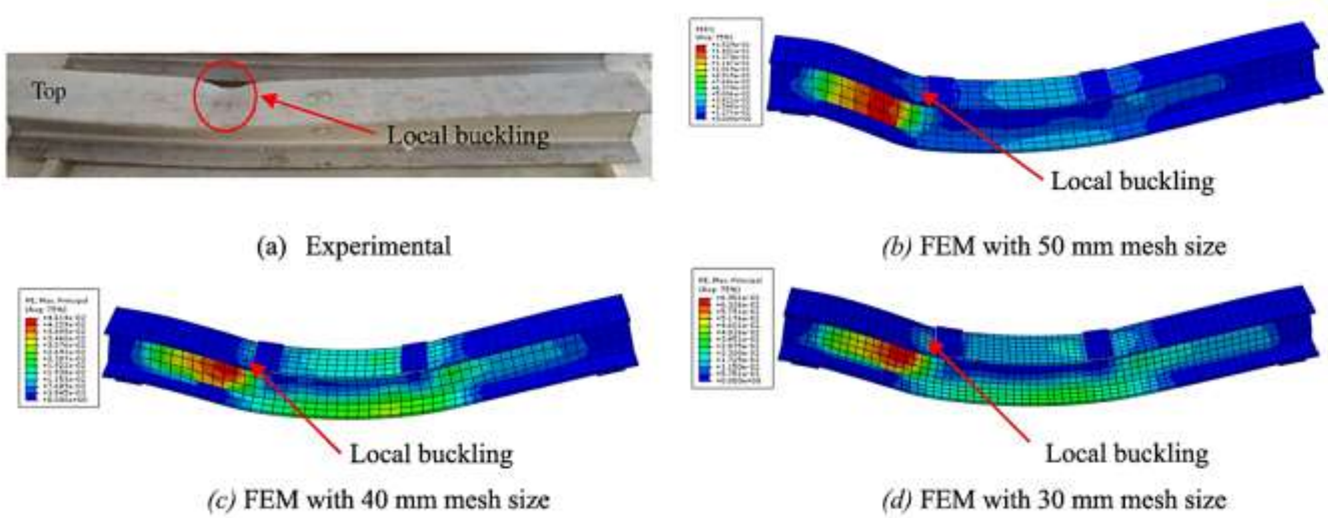



Fig. 3. Effect of the numerical mesh size on the failure pattern (Mansour et al., 2022).

To evaluate the performance of these strengthened beams, four-point bending tests are typically employed, simulating the loading conditions observed in hogging moment zones of continuous beams. The experimental setup includes two-point loads applied symmetrically to generate constant moment regions, enabling researchers to observe the progression of cracking and failure mechanisms. Studies conducted by Zhang et al. (2020) have shown that this testing configuration replicates the behavior of continuous composite beams with considerable accuracy. Instrumentation plays a critical role in these experiments, with strain gauges installed strategically on the steel girder, concrete slab, and CFRP laminates to measure stress distribution and strain. Additionally, displacement transducers record the mid-span deflection, while cameras capture the initiation and propagation of cracks during loading.

The load-deflection behavior of CFRP-integrated beams has revealed significant improvements in flexural performance. Liu et al. (2022) reported that applying CFRP laminates delayed the onset of steel yielding and enhanced the ultimate load capacity. Single-layer laminates demonstrated an 18% increase in capacity compared to unreinforced beams, while double-layer configurations achieved improvements of up to 22%. Despite these enhancements, the ductility of the beams was observed to decrease with an increasing number of CFRP layers, underscoring the need for balance between strength and flexibility during the design process. Failure modes in these beams typically began with the yielding of steel reinforcement, the flexure of CFRP laminates, and finally, diagonal cracking near the supports. Such findings align with those observed by Katwal et al. (2018) who emphasized the importance of preventing premature debonding to achieve optimal performance. Fig. 4 displays the load versus deflection curves based on the study conducted by Sakr et al. (2018).

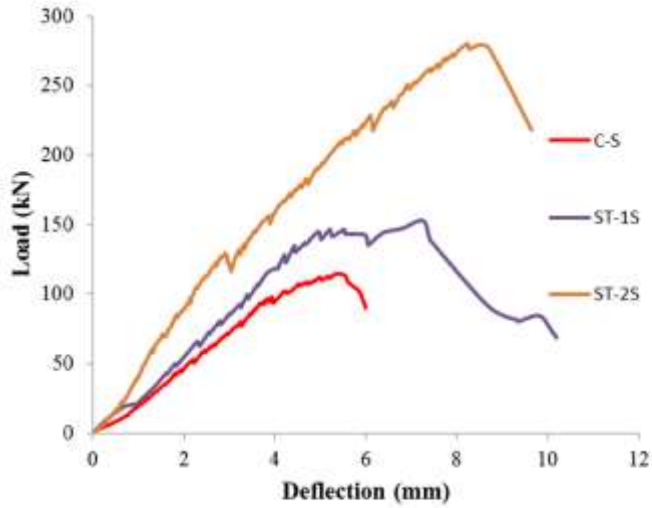



Fig. 4. Load-deflection curve for beam specimens (Sakr et al., 2018).

The level of shear connection between the steel girder and the concrete slab was another critical parameter investigated in experimental studies. Beams with full shear connection exhibited superior composite action, enabling better utilization of CFRP strength. In contrast, beams with partial shear connection showed greater slip at the interface, leading to reduced load-carrying capacity and stiffness. Abushanab et al. (2022) highlighted the importance of ensuring adequate shear transfer mechanisms, particularly in beams retrofitted with CFRP in regions of high tensile stress. Additionally, CFRP laminates' configuration and application method significantly influenced the overall structural behavior. Hybrid bonding techniques, combining mechanical anchorage with adhesive bonding, have shown promise in mitigating the risk of debonding. This method ensures a more reliable stress transfer, as noted in experimental findings by El-Zohairy et al. (2017).

The presence of the laminates significantly mitigates crack propagation in CFRP-strengthened beams. Researchers have consistently observed that CFRP delays the initiation of cracks and reduces their width and spacing. In hogging moment zones, where tensile stresses are concentrated, CFRP acts as a supplemental tensile reinforcement, redistributing stresses and preventing sudden failure. This behavior has been corroborated by experimental programs conducted on full-scale and laboratory-scale specimens. The use of strain gauges and high-resolution imaging has further validated these observations, providing quantitative data on the effectiveness of CFRP in crack control.

**4. FE modeling of SCC-beams with CFRP**

The primary objective of the FE investigation is to create a numerical model capable of simulating the nonlinear flexural behavior of both strengthened and unreinforced beams. The FE modeling provides additional detailed data that were not seen during the actual testing and examines the influence of various factors on beam capacity. Mansour et al. (2022) used 3D surface-to-surface contact-pair components in their work to model the interface involving concrete flanges and laminates made of CFRP, which is illustrated in Fig. 5. They used CONTA174 and TARGE170 components in ANSYS to represent the touch and impact surfaces, accordingly. CONTA174 was used to model the sliding interaction between the CFRP lamination surfaces of contact and the flexible concrete flange, while TARGE170 was applied to discretize the target surface. The model assumed complete adhesion between the two surfaces, with the CFRP laminates as the contact surface and the concrete flange as the target surface. The research further included the mesh shape, loading configuration, and the shear connector and beam-slab contact specifics.

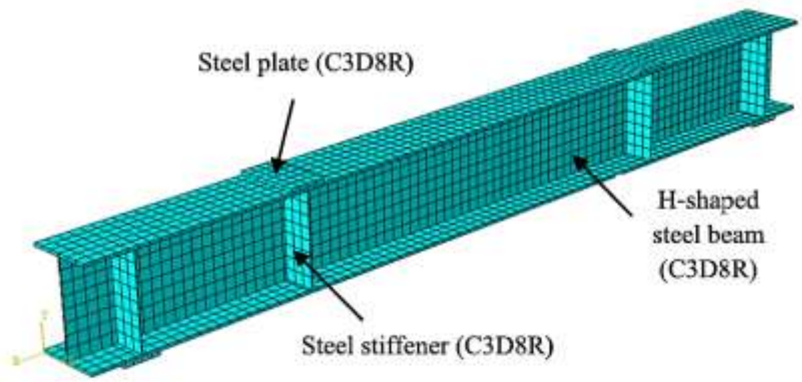



Fig. 5. FE mesh used to modeling a SC composite beam (Mansour et al., 2022).

### *4.1 Modeling Approach*

In FE modeling, the steel beam, concrete slab, and CFRP reinforcement are represented using distinct material models and element types that capture their individual mechanical behaviors. The steel beam is typically modeled using beam elements representing the bending and axial response. The concrete slab is modeled using shell elements, which can capture both in-plane and out-of-plane deformations. CFRP reinforcement is usually represented as shell or solid elements, depending on the geometry of the CFRP layers and the desired level of detail in capturing the material response. The shear connectors, which transfer forces between steel and concrete elements, are modeled using link elements that can capture the force transfer at the steel-concrete interface. The interaction between the steel and concrete components is modeled using contact elements such as TARGE170 (in ANSYS), which represent the contact and target surfaces, respectively. These elements account for the shear transfer and slip behavior between the materials. The CFRP layers are modeled with a focus on bond-slip behavior, where interface elements or coupling models are employed to capture the load transfer between the CFRP and concrete and any debonding that may occur at the interface. However, Table 1 discusses the previous studies conducted on FE analysis of SCC beams.

Table 1. Studies based on the application of FE modeling on steel-concrete composite structures.

| Reference | Structure Type | FE Modeling | Outcomes |
|---|---|---|---|
| (Liu et al., 2022) | Continuous steel-concrete composite beams | Nonlinear modeling with hybrid bonding (adhesive and mechanical) | Improved load capacity (22% with double-layer CFRP), mitigated debonding. |
| (Peiris & Harik, 2021) | Prestressed steel-concrete composite beams | Modeled unbonded retrofit systems with prestressing | Increased yielding and ultimate load, reduced prestress loss (<3%). |
| (El-Zohairy et al., 2017) | Continuous composite beams under hogging moment regions | Parametric study on CFRP thickness, bond length | Accurate load-deflection prediction; enhanced stiffness, reduced ductility. |
| (Barour et al., 2020) | Retrofitted beams with various CFRP layers | Validated FE models for crack propagation and flexural response | Single-layer CFRP improved capacity by 18%; two layers by 22%. |
| (Abushanab et al., 2022) | Experimental and theoretical analysis of composite beams | Detailed nonlinear simulations of bond interaction | Delayed crack propagation; enhanced failure control at hogging moments. |
| (De Domenico et al., 2014) | Continuous beams with web openings | 3D non-linear FEM for retrofitting with FRP strips | Strengthening restored stiffness and enhanced load-carrying capacity. |
| (Raji et al., 2022) | Simply supported composite beams | Hybrid bonded FRP modeling | Eliminated premature debonding, enhanced flexural capacity. |
| (Pang et al., 2021) | Two-span continuous composite girders | Bonded CFRP laminates with FE model | Enhanced cracking resistance and composite action at hogging moments. |
| (Kadhim et al., 2020) | Steel-concrete composite girders | Clamping CFRP ends in FE simulations | Improved ductility and reduced premature debonding risks. |
| (Diab et al., 2021) | Hybrid FRP retrofitted structures | FE model integrating mechanical fasteners | Superior bond strength, delayed crack initiation, and failure modes improved. |
| (Al-Saawani et al., 2022) | Composite beams with varying CFRP layers | Nonlinear finite element simulations | CFRP layer thickness correlated to increased stiffness and ultimate capacity. |

| | | | |
|---|---|---|---|
| (Jasim et al., 2020) | Embedded reinforcement using CFRP | Parametric FE study on embedded ends | Improved bonding performance and elimination of debonding failures. |

#### *4.2 Material Properties*

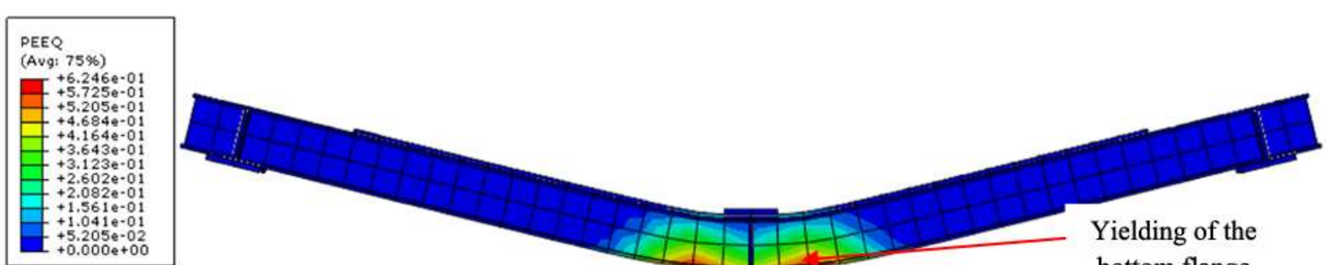
The material attributes of the steel, concrete, and CFRP need to be defined accurately to ensure the accuracy of the FE model. Steel is typically simulated as a linear elastic material with a yield strength and modulus of elasticity that represent its stress-strain behavior. Concrete, on the other hand, exhibits non-linear behavior under compression, and therefore, a non-linear concrete material model is often employed (e.g., concrete damaged plasticity model in ABAQUS) to simulate cracking and plastic deformation. CFRP composites are generally modeled as anisotropic materials with high tensile strength and low compressive strength. The transverse shear modulus and Poisson's ratio for CFRP are particularly important for accurately capturing its behavior under bending and shear loading. In addition to the material properties of the individual components, the bonding strength between the CFRP and concrete, as well as the stiffness and spacing of the shear connectors, play a crucial role in the overall behavior of the composite beam system. These parameters are typically calibrated using experimental data.

#### *4.3 Boundary Conditions and calibration*

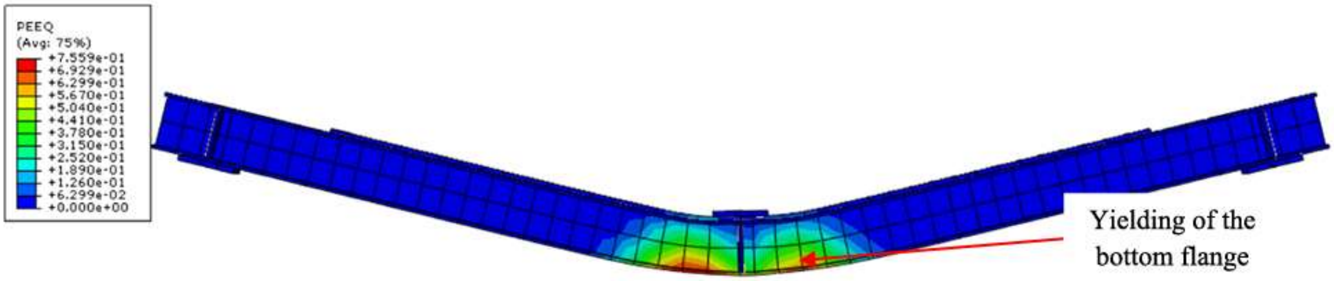
The boundary conditions of the FE model are established based on the real-world constraints of the composite beam. For instance, the simply supported or fixed boundary conditions are applied at the beam's ends to simulate the support conditions. The model also considers point loads, uniformly distributed loads, or moment-curvature relationships to simulate realistic loading scenarios. Prestressing forces in the CFRP layers may be included for scenarios involving externally bonded CFRP, which further complicates the boundary condition definition. To ensure the accuracy of the FE model, it is calibrated against experimental data from beam bending tests and shear tests. Common validation approaches include comparing the predicted deflections, strain distributions, and failure modes with experimental results. The FE model is refined iteratively, adjusting material properties and element types to match the observed behavior. Sensitivity analysis is also employed to investigate the influence of parameters such as CFRP lay-up configurations, shear connector spacing, and interface bond strength on the overall beam response.

#### *4.4 FE modeling criteria and mesh size*

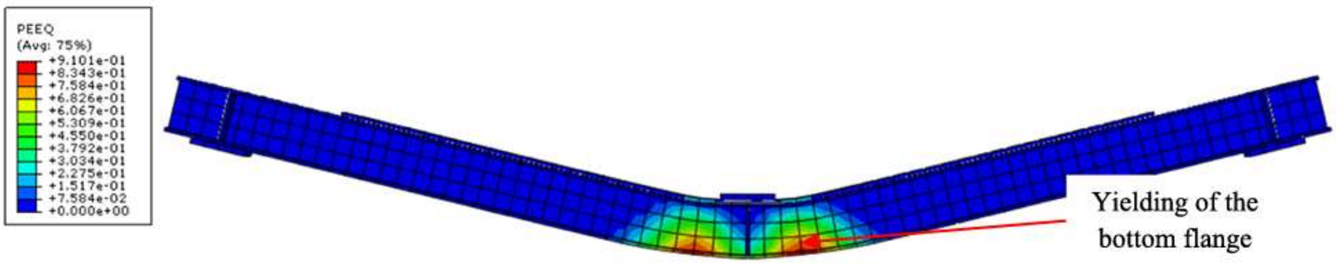
In FE modeling of steel column composite beams, the interaction between the steel beam, concrete slab, and shear connectors is critical to accurately simulate composite action under various loading conditions. Typically, the steel column is modeled using beam or shell elements, while the concrete slab can be represented using shell or solid elements, depending on the complexity of the beam geometry. Shear connectors, which transfer forces between the steel and concrete components, are modeled using link or connector elements. These connectors are essential for representing the bond between the two materials and for ensuring the accurate transfer of forces in the composite beam. According to Mansour et al. (2022), the FE model they developed for the steel column composite beam effectively captures the behavior of the beam under both static and dynamic loads. The authors emphasized the importance of modeling the shear connectors with high accuracy, as these connectors play a significant role in transferring shear forces between the steel beam and concrete slab. Their study demonstrated that the stiffness and arrangement of shear connectors directly influence the load distribution, the overall bending moment resistance, and the beam's stability. This particular FE modeling approach allowed them to replicate the real-world behavior of composite beams more accurately than traditional analytical methods. Their approach accounts for the complexities of the material interfaces and the non-linear interaction between the steel and concrete components, which needs to be addressed in simpler models. Fig. 6 demonstrates the impact of mesh size on the deformation of FE model beams.




(a) FEM having a mesh size of 50mm




(b) FEM having a mesh size of 40mm




(c) FEM having a mesh size of 30mm

Fig. 6. Impact of mesh size on the failure behavior of FE models (Mansour et al., 2022).

In another study, Hawileh et al. (2019) found that the long-term effects, such as concrete creep and shrinkage, significantly impacted the deflection and stress distribution in composite beams over time. Their model was calibrated to consider these time-dependent properties, along with the non-linear behavior of the shear connectors, which allowed them to predict the long-term performance of the composite beams under sustained loading. The study highlighted that shear connectors with higher stiffness reduced the deflection and increased load-carrying capacity, while more distributed connector arrangements provided a more uniform stress distribution.

**5. Limitations and future recommendations**

One significant limitation of current FEM approaches is the simplification of material models. While these models are computationally efficient, they may fail to fully capture the complex non-linearities observed under high-stress states, such as cracking, spalling, and concrete crushing. Additionally, CFRP reinforcement is often modeled as a purely linear elastic material with a high tensile strength, neglecting the transverse effects, inelastic behavior, and interface debonding that can significantly impact the composite beam's performance. The interface modeling between CFRP and concrete also remains a challenge. Although recent studies have employed bond-slip models to represent the interaction, debonding failures and shear slip behavior are often modeled in a simplified manner, neglecting complex real-world phenomena such as moisture effects, environmental degradation, and aging of the adhesive material. Moreover, interface failure due to fatigue loading and cyclic stresses is not always comprehensively addressed in current models, which limits the predictive accuracy of the long-term performance of CFRP-strengthened SC beams.

Another limitation arises from the calibration and validation of FEM models. Although several studies have validated their models against experimental results, discrepancies often arise due to variations in experimental conditions, such as differences in loading rates, temperature effects, or material heterogeneity. Sensitivity analyses are often used to address this. However, the results may still be subject to uncertainties in material properties and boundary conditions, which may not perfectly reflect real-world conditions.

Future studies should focus on developing more sophisticated material models for CFRP and concrete that incorporate inelastic behavior, transverse shear effects, and failure criteria under dynamic and fatigue loading. The non-linear behavior of CFRP, such as rupture, delamination, and creep, needs to be modeled with greater accuracy. Similarly, concrete models should integrate damage mechanics and fracture mechanics to simulate better cracking, spalling under high compressive stress, and the hygrothermal effects on concrete properties over time. Using multi-scale modeling approaches could be an important step forward in understanding composite beams' microstructural and macrostructural behavior. Recent studies have focused on the mesoscale behavior of shear connectors and the micro-mechanics of CFRP-concrete interfaces. Future studies could use multi-scale finite element models that consider the microscopic behavior of materials at the level of individual fibers in the CFRP and the nano-mechanical properties of the concrete matrix. This would improve the accuracy of the simulations, particularly in predicting failure modes and local stress distributions in CFRP-strengthened systems.

Long-term performance and durability under fatigue loading are areas that require more attention. As the application of CFRP in composite beams often aims to improve the service life of structures, it is crucial to incorporate fatigue analysis into FEM. Research could explore the cyclic loading behavior of composite beams, including the influence of repeated stress cycles on the CFRP-concrete interface and shear connectors, which are critical for predicting fatigue-induced failures. Environmental effects, such as moisture, temperature fluctuations, and chemical degradation, also need to be considered more comprehensively to better model the long-term durability of CFRP-reinforced SC beams.

## 6. Conclusions

This review paper has highlighted the significant advancements in the application of FEM to analyze SCBB reinforced with CFRP. FEM has been widely adopted as an essential tool for simulating the complex interactions between the constituent materials, including steel, concrete, and shear connectors. The ability of FEM to predict key structural behaviors, such as deflection, stress distribution, and failure modes, has made it invaluable in the design and optimization of SCBs. While significant progress has been made in modeling the steel-concrete interaction, the integration of CFRP reinforcement has introduced additional complexities, particularly in accurately modeling the non-linear behavior of CFRP and its interaction with the concrete slab. Existing FEM approaches often simplify the CFRP as a linear elastic material, overlooking critical phenomena such as delamination, rupture, and interface debonding under high tensile and cyclic loading conditions. Moreover, while shear connectors are typically modeled as elastic link elements, their non-linear behavior remains inadequately addressed, especially under cyclic and fatigue loading. This limits the predictive capabilities of current FEM models in representing the long-term durability and performance of CFRP-strengthened SCCB.

The review also highlights the need for future research to enhance the accuracy and reliability of FEM for CFRP-strengthened composite beams. A major area for improvement is the interface modeling between CFRP and concrete, particularly the bond-slip behavior, which is critical in predicting failure modes and the load transfer mechanism. Additionally, multi-scale modeling that captures both the macrostructural behavior of composite materials will be crucial for more precise simulations. Future studies should also incorporate advanced material models that account for CFRP's non-linear, fatigue, and creep behavior under dynamic loading. Finally, while FEM has been validated against experimental data, there remains a gap in full-scale testing under real-world conditions. Validating FEM predictions with field data will improve the accuracy of simulations and enhance the design and optimization of CFRP-reinforced SCBs for practical applications, ensuring these structures perform reliably in diverse and challenging environments.

**Funding**: This research received no external funding.
**Conflicts of Interest**: The authors declare no conflict of interest.
**ORCID:** 0009-0006-9843-7842


## References

[1] Abushanab, A., Alnahhal, W., & Farraj, M. (2022). Experimental and finite element studies on the structural behavior of BFRC continuous beams reinforced with BFRP bars. *Composite Structures*, *281*, 114982.

[2] Ahmed, E., & Sobuz, H. R. (2011a). Experimental study on long-term behaviour of CFRP strengthened RC beams under sustained load. *Structural engineering and mechanics: An international journal*, *40*(1), 105-120.

[3] Ahmed, E., & Sobuz, H. R. (2011b). Flexural and time-dependent performance of palm shell aggregate concrete beam. *KSCE Journal of Civil Engineering*, *15*(5), 859-865. https://doi.org/10.1007/s12205-011-1148-2

[4] Ahmed, E., & Sobuz, H. R. (2011c). Immediate and long-term deflection of carbon fiber reinforced polymer (CFRP) concrete beams. *Key Engineering Materials*, *471*, 73-78.

[5] Akid, A. S. M., Shah, S. M. A., Sobuz, M. D. H. R., Tam, V. W. Y., & Anik, S. H. (2021). Combined influence of waste steel fibre and fly ash on rheological and mechanical performance of fibre-reinforced concrete. *Australian Journal of Civil Engineering*, *19*(2), 208-224. https://doi.org/10.1080/14488353.2020.1857927

[6] Akid, A. S. M., Wasiew, Q. A., Sobuz, M. H. R., Rahman, T., & Tam, V. W. (2021). Flexural behavior of corroded reinforced concrete beam strengthened with jute fiber reinforced polymer. *Advances in Structural Engineering*, *24*(7), 1269-1282. https://doi.org/10.1177/1369433220974783

[7] Al-Saawani, M. A., Al-Negheimish, A. I., El-Sayed, A. K., & Alhozaimy, A. M. (2022). Finite element modeling of debonding failures in FRP-strengthened concrete beams using cohesive zone model. *Polymers*, *14*(9), 1889.

[8] Barour, S., Zergua, A., Bouziadi, F., & Abed Jasim, W. (2020). Finite element analysis of CFRP-externally strengthened reinforced concrete beams subjected to three-point bending. *World Journal of Engineering*, *17*(2), 183-202.

[9] De Domenico, D., Fuschi, P., Pardo, S., & Pisano, A. A. (2014). Strengthening of steel-reinforced concrete structural elements by externally bonded FRP sheets and evaluation of their load carrying capacity. *Composite Structures*, *118*, 377-384. https://doi.org/https://doi.org/10.1016/j.compstruct.2014.07.040

[10] Diab, H., Khaled, T., & Rashwan, M. (2021). Flexural behavior of RC continuous T-beams reinforced with hybrid CFRP/steel bars (experimental and numerical study). *JES. Journal of Engineering Sciences*, *49*(2), 215-247.

[11] Ekmekyapar, T., & Al-Eliwi, B. J. M. (2016). Experimental behaviour of circular concrete filled steel tube columns and design specifications. *Thin-Walled Structures*, *105*, 220-230. https://doi.org/https://doi.org/10.1016/j.tws.2016.04.004

[12] El-Zohairy, A., Salim, H., Shaaban, H., Mustafa, S., & El-Shihy, A. (2017). Experimental and FE parametric study on continuous steel-concrete composite beams strengthened with CFRP laminates. *Construction and Building Materials*, *157*, 885-898.

[13] Fahmy, E. (1996). Analysis of composite beams with rectangular web openings. *Journal of Constructional Steel Research*, *37*(1), 47-62.

[14] Gotame, M., Franklin, C. L., Blomfors, M., Yang, J., & Lundgren, K. (2022). Finite element analyses of FRP-strengthened concrete beams with corroded reinforcement. *Engineering Structures*, *257*, 114007. https://doi.org/https://doi.org/10.1016/j.engstruct.2022.114007

[15] Hawileh, R., Musto, H., Abdalla, J., & Naser, M. (2019). Finite element modeling of reinforced concrete beams externally strengthened in flexure with side-bonded FRP laminates. *Composites Part B: Engineering*, *173*, 106952.

[16] Jasim, W. A., Tahnat, Y. B. A., & Halahla, A. M. (2020). Behavior of reinforced concrete deep beam with web openings strengthened with (CFRP) sheet. Structures,

[17] Kadhim, M. M., Jawdhari, A. R., Altaee, M. J., & Adheem, A. H. (2020). Finite element modelling and parametric analysis of FRP strengthened RC beams under impact load. *Journal of Building Engineering*, *32*, 101526.

[18] Kang, L., Fan, W., Liu, B., & Liu, Y. (2021). Numerically efficient analysis of concrete-filled steel tubular columns under lateral impact loading. *Journal of Constructional Steel Research*, *179*, 106564. https://doi.org/https://doi.org/10.1016/j.jcsr.2021.106564

[19] Katwal, U., Tao, Z., & Hassan, M. K. (2018). Finite element modelling of steel-concrete composite beams with profiled steel sheeting. *Journal of Constructional Steel Research*, *146*, 1-15. https://doi.org/https://doi.org/10.1016/j.jcsr.2018.03.011

[20] Liu, X., Tang, L., Jing, Y., Xiang, J., Tian, X., Liu, W., Huang, Y., Zhang, G., Zhao, W., & Yang, G. (2022). Behaviour of continuous steel–concrete composite beams strengthened with CFRP sheets at hogging-moment region. *Composite Structures*, *291*, 115695. https://doi.org/https://doi.org/10.1016/j.compstruct.2022.115695

[21] Loqman, N., Safiee, N. A., Bakar, N. A., & Nasir, N. A. M. (2018). Structural behavior of steel-concrete composite beam using bolted shear connectors: A review. MATEC Web of Conferences,

[22] Madenci, E., Fayed, S., Mansour, W., & Özkılıç, Y. O. (2022). Buckling performance of pultruded glass fiber reinforced polymer profiles infilled with waste steel fiber reinforced concrete under axial compression. *Steel and Composite Structures, An International Journal*, *45*(5), 653-663.

[23] Mansour, W. (2021). Numerical analysis of the shear behavior of FRP-strengthened continuous RC beams having web openings. *Engineering Structures*, *227*, 111451.

[24] Mansour, W., Tayeh, B. A., & Tam, L.-h. (2022). Finite element analysis of shear performance of UHPFRC-encased steel composite beams: Parametric study. *Engineering Structures*, *271*, 114940.

[25] Pang, M., Shi, S., Hu, H., & Lou, T. (2021). Flexural behavior of two-span continuous CFRP RC beams. *Materials*, *14*(22), 6746.

[26] Peiris, A., & Harik, I. (2021). Steel beam strengthening with UHM CFRP strip panels. *Engineering Structures*, *226*, 111395. https://doi.org/https://doi.org/10.1016/j.engstruct.2020.111395

[27] Raji, A., Mostofinejad, D., & Eftekhar, M. R. (2022). A novel parallel wire steel-reinforced mortar (PW-SRM) method versus textile reinforced mortar (TRM) for out-of-plane strengthening of masonry walls. *Journal of Building Engineering*, *57*, 104806. https://doi.org/https://doi.org/10.1016/j.jobe.2022.104806

[28] Rana, M. J., Hasan, M. R., & Sobuz, M. H. R. (2022). An investigation on the impact of shading devices on energy consumption of commercial buildings in the contexts of subtropical climate. *Smart and Sustainable Built Environment*, *11*(3), 661-691. https://doi.org/10.1108/SASBE-09-2020-0131

[29] Sakr, M. A., Sleemah, A. A., Khalifa, T. M., & Mansour, W. N. (2018). Behavior of RC beams strengthened in shear with ultra-high performance fiber reinforced concrete (UHPFRC). MATEC web of conferences,

[30] Sobuz, H. R., Ahmed, E., & Sutan, N. M. (2011). Deflection and cracking behavior of RC beams externally reinforced with carbon fiber laminates. *Journal of reinforced plastics and composites*, *30*(21), 1807-1818.

[31] Wang, A. J., & Chung, K. F. (2008). Advanced finite element modelling of perforated composite beams with flexible shear connectors. *Engineering structures*, *30*(10), 2724-2738.

[32] Wu, M., Fan, S., Zhou, H., Han, Y., & Liang, D. (2022). Experimental and numerical research on fire resistance of stainless steel-concrete composite beam. *Journal of Constructional Steel Research*, *194*, 107342. https://doi.org/https://doi.org/10.1016/j.jcsr.2022.107342

[33] Xu, Y., Tang, H., Chen, J., Jia, Y., & Liu, R. (2021). Numerical analysis of CFRP-confined concrete-filled stainless steel tubular stub columns under axial compression. *Journal of Building Engineering*, *37*, 102130. https://doi.org/https://doi.org/10.1016/j.jobe.2020.102130

[34] Zhang, J., Hu, X., Fu, W., Du, H., Sun, Q., & Zhang, Q. (2020). Experimental and theoretical study on longitudinal shear behavior of steel-concrete composite beams. *Journal of Constructional Steel Research*, *171*, 106144.

[35] Zhu, Z.-h., Zhang, L., Bai, Y., Ding, F.-x., Liu, J., & Zhou, Z. (2016). Mechanical performance of shear studs and application in steel-concrete composite beams. *Journal of Central South University*, *23*(10), 2676-2687. https://doi.org/10.1007/s11771-016-3329-0