Integrating Composite Retrofitting into Structural Design Education: A Hands-On Approach to Learning with Fiber-Reinforced Polymers

David Olusogo Owolabi, Morgan State University

David Owolabi is a PhD student in civil engineering at Morgan State University, specializing in resilience and sustainable engineering for critical infrastructure. His academic journey focuses on advancing his knowledge in structural engineering and construction management, with the goal of becoming a leading expert in these fields. David's primary research area is on the development of innovative sustainable materials, such as self-healing concrete known as bioconcrete. David's work explores the integration of green materials, lifecycle assessment, and resilient engineering practices in construction. In his other research areas, he also seeks to address key challenges in infrastructure sustainability while promoting long-term resilience in construction.

Dr. Mehdi Shokouhian, Morgan State University

Dr. Shokouhian is an Associate Professor at the Department of Civil Engineering, Morgan State University. He earned his Ph.D. in structural engineering from Tsinghua University in 2015. He conducts integrated experimental and analytical research on innovative structures and high performance materials. Dr. Shokouhian has been principal and co-principal investigator on many projects funded by federal and state agencies exceeding $2M. He published more than 100 peer-reviewed journal articles, conference papers, and technical reports. He has served as editorial board member and reviewer for more than 20 international and national refereed journals.

Benjamin Gbeminiyi Famewo, Morgan State University

Benjamin Famewo is a Ph.D. Candidate in Civil Engineering at Morgan State University. He holds a Bachelor's and Master's degree in Civil Engineering and has professional experience as a structural engineering intern, contributing to reinforced concrete design and rehabilitation projects.

Izhar Ahmad, Morgan State University

Integrating Composite Retrofitting into Structural Design Education: A Hands-On Approach to Learning with Fiber-Reinforced Polymers

Abstract.

This paper presents a hands-on design-learning initiative that integrates composite retrofitting into undergraduate structural engineering education. The project aimed to strengthen students' understanding of design decision-making, material behavior, and real-world structural performance through direct engagement with fiber-reinforced polymers (FRPs). Two cohorts of undergraduate students participated in the activity, where they designed and fabricated composite systems using the hand lay-up process. In the first phase, students retrofitted scaled timber beams with glass fiber-reinforced polymer (GFRP) sheets, comparing partial wrapping at the mid-span to full-length wrapping strengthening configurations. A second group applied similar GFRP wrapping strategies to concrete cylinders under compression loading as well as gaining experience in concrete mix design, specimen preparation, curing, and subsequent composite application. Each team was responsible for designing the wrapping configuration, preparing and applying the epoxy-hardener system, and testing the specimens using a Universal Testing Machine (UTM) to evaluate flexural or compressive strength. The activity encouraged students to compare their design choices, partial versus full wrapping, and analyze performance trade-offs based on experimental results. The students also learned the challenges of delamination due to improper application of epoxy with the GFRP. Post-activity surveys revealed significant gains in students' confidence with structural design, materials selection, retrofitting strategies, and safety-conscious lab practices. This paper discusses how integrating composite retrofitting into design education cultivates hands-on problem solving, critical reflection, and appreciation of modern materials in structural engineering. By embedding composite fabrication and testing within a design education framework, this activity bridges the gap between theory and practice. It demonstrates how experiential, project-based learning can deepen students' conceptual understanding of structural design while cultivating essential engineering design skills and professional competencies. ***Student learning outcomes were assessed through analysis of student laboratory reports, design justifications, and experimental interpretations submitted at the conclusion of the activity.***

1. Introduction

Structural retrofitting plays a vital role in extending the service life, safety, and performance of aging infrastructure systems. Many existing timber and reinforced concrete structures were designed under outdated codes or are now subjected to increased service demands, environmental degradation, and changing functional requirements. As a result, modern strengthening and rehabilitation techniques have become essential in contemporary civil and structural engineering practice. Among these techniques, fiber-reinforced polymers (FRPs) have gained widespread adoption due to their high strength-to-weight ratio, corrosion resistance, constructability, and minimal impact on structural geometry [1], [2], [3]. FRP systems have been successfully applied to strengthen and rehabilitate concrete, timber, masonry, and steel structures, improving flexural capacity, confinement, and overall structural performance. Despite the increasing use of FRP systems in professional practice and design standards, undergraduate structural engineering education continues to emphasize analytical design methods and code-based procedures for new construction, often with limited exposure to modern materials and retrofitting techniques. Students typically learn the theoretical behavior of structural members and materials in isolation, with few opportunities to connect design assumptions to fabrication challenges, material behavior, and real-world performance. This gap between theory and practice can limit students' ability to fully appreciate constructability constraints, material limitations, and performance-based design considerations associated with advanced composite systems [4], [5].

Engineering education research has consistently demonstrated that experiential, active, and project-based learning approaches enhance students' conceptual understanding, engagement, and ability to transfer theoretical knowledge to practical applications [6], [7]. Hands-on activities that involve fabrication, testing, and iterative design decisions enable students to directly observe structural behavior and failure mechanisms that are difficult to convey through lectures alone [8], [9]. In structural engineering education, laboratory experiences are particularly effective for reinforcing abstract concepts such as load transfer, stiffness, ductility, failure modes, and material interaction [10], [11]. However, many traditional laboratory exercises focus primarily on conventional materials such as steel and reinforced concrete, offering limited opportunities for students to engage with advanced composite materials and modern retrofitting strategies [12]. The disconnect between classroom instruction and contemporary structural engineering practice presents a significant pedagogical challenge. While current design codes and professional guidelines increasingly incorporate FRP-based strengthening methods, students often graduate without meaningful exposure to composite fabrication techniques, bonding behavior, or the constructability challenges associated with retrofitting existing structural members [13], [14]. As a result, students may struggle to develop informed design judgment when selecting strengthening strategies or evaluating performance trade-offs among different retrofitting configurations. Integrating FRP retrofitting into design-oriented coursework offers a promising pathway to address this gap by combining material science, structural behavior, and hands-on decision-making within a single learning experience.

This paper presents a hands-on design-learning initiative that integrates composite retrofitting into undergraduate structural engineering coursework through the fabrication, strengthening, and testing of scaled structural elements. The activity was implemented across two cohorts of undergraduate students and involved the design and application of glass fiber-reinforced polymer (GFRP) systems using a hand lay-up process. Students retrofitted timber beams subjected to flexural loading and concrete cylinders tested under compression, enabling exploration of composite behavior across different structural materials and loading conditions. By comparing partial and full wrapping configurations, students were encouraged to evaluate the effectiveness, efficiency, and limitations of different strengthening strategies based on experimental performance.

The educational objectives of this initiative were to (1) enhance students' understanding of composite material behavior and FRP retrofitting principles, (2) strengthen design decision-making through direct experimentation and performance comparison, and (3) cultivate professional competencies related to laboratory safety, constructability, and critical reflection. Through direct engagement with specimen preparation, epoxy application, curing, testing procedures, and failure analysis, students gained insight into both the benefits and challenges of FRP retrofitting, including issues such as debonding and delamination resulting from improper bonding practices [15], [16]. Assessment results and post-activity surveys indicate that the hands-on approach significantly improved students' confidence in structural design, materials selection, and real-world problem solving.

By embedding composite fabrication and experimental testing within a design education framework, this work demonstrates how experiential learning can effectively bridge the gap between theory and practice in structural engineering education. The findings contribute to ongoing efforts within engineering education to modernize curricula, promote active learning, and better prepare students for professional practice involving advanced materials and infrastructure rehabilitation.

2. Literature Review

Fibre-reinforced polymer (FRP) composites are relatively modern construction materials that have been employed in buildings and bridge infrastructure for more than five decades. Their application, however, predates their use in civil engineering; FRPs were first introduced in the 1930s within the marine, automotive, and aerospace industries due to their favorable mechanical properties and lightweight characteristics [17]. Since then, their use has expanded to rail transportation, sports equipment, and wind energy systems. Currently, the construction sector accounts for approximately one-quarter of global FRP production, highlighting the growing importance of these materials in civil infrastructure applications [18], [19]. Figure 1 illustrates the distribution of FRP market share across various industries. FRP composites are composed of high-strength fibers embedded within a polymer resin matrix. For structural applications, the most used fibers include glass, carbon, and aramid, while the matrix is typically made of polyester, vinyl ester, or epoxy resins. The fibers provide the primary load-carrying capacity, contributing strength and stiffness, whereas the resin binds the fibers together, facilitates stress transfer, and protects them from environmental and mechanical damage [17].

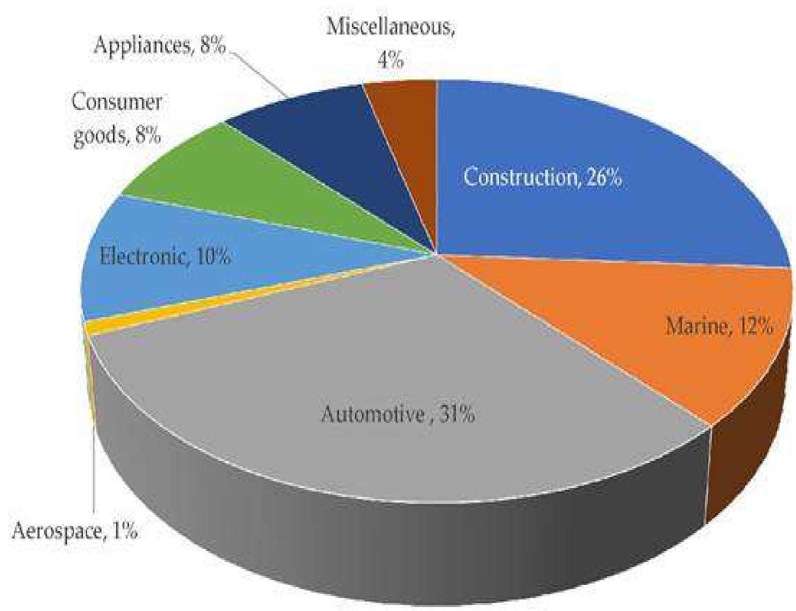


Figure 1: Market share of Fibre Reinforced Polymer (FRP) by application [20].

Over the past few decades, FRP composites have gained significant attention in structural engineering practice due to their high strength-to-weight ratio, superior corrosion resistance, and versatility in both new construction and rehabilitation applications. Unlike conventional steel reinforcement, FRP materials generally exhibit linear-elastic behavior up to failure and lack a distinct yield point, resulting in brittle failure modes. While this characteristic introduces design challenges particularly with respect to ductility and energy dissipation it also offers opportunities for innovative structural solutions when appropriately addressed through design guidelines and hybrid systems [20].

2.1. Applications of Fiber-Reinforced Polymers in Construction

Due to their high tensile strength, low self-weight, superior corrosion resistance, and ease of installation, fiber-reinforced polymers (FRPs) have been widely adopted in construction to enhance the flexural, shear, and axial capacities of structural members without significantly increasing dead load or altering existing member geometry [1], [2], [3]. These advantages make FRP systems particularly attractive for both new construction and rehabilitation of aging infrastructure.

FRP applications in civil engineering can be broadly categorized into three main groups: (i) FRP structural profiles used in new construction, (ii) FRP reinforcements - such as bars, tendons, and grids embedded within concrete, and (iii) externally bonded or near-surface mounted FRP systems used for strengthening and retrofitting existing structural elements. Among available materials, glass fiber-reinforced polymer (GFRP) is the most commonly utilized due to its cost-effectiveness, corrosion resistance, and ease of manufacture, while carbon fiber-reinforced polymer (CFRP) provides higher stiffness and superior specific strength at a higher material cost [20]. FRP composites have been employed in fully FRP-based structural components, including beams, columns, bridge decks, and pedestrian bridges, particularly in aggressive environments where conventional materials are susceptible to corrosion, such as coastal and marine regions. Pultruded FRP profiles, in particular, enable the construction of lightweight structural systems with reduced transportation demands and rapid on-site assembly [20], [21], [22]. Despite these advantages, challenges related to connection detailing, joint behavior, fire performance, and long-term durability continue to be areas of active research.

In reinforced concrete applications, GFRP and CFRP bars have been extensively investigated as alternatives to traditional steel reinforcement to address corrosion-induced deterioration. Numerous studies have examined the mechanical behavior of FRP-reinforced concrete beams and columns, considering parameters such as concrete strength, fiber type, reinforcement ratio, and loading conditions. While these systems demonstrate improved durability and resistance to environmental degradation, their lower elastic modulus relative to steel often results in increased deflections and serviceability concerns that must be accounted for in design [23], [24] , [25].

2.2. FRP in Strengthening and Repair Applications

Fiber-reinforced polymer (FRP) composites have been extensively employed for the repair and strengthening of existing structures due to their high strength-to-weight ratio, corrosion resistance, and adaptability to various structural materials. Externally bonded FRP reinforcement systems are widely used to enhance the performance of concrete, timber, steel, and masonry structures, offering an efficient means of upgrading structural capacity without significant increases in self-weight or disruption to serviceability [25]. The development of design guidelines, such as ACI 440, has provided standardized procedures for the design and installation of FRP strengthening systems for reinforced concrete structures, thereby facilitating their acceptance and implementation in professional practice [26]. Externally bonded FRP sheets and plates, as well as near-surface mounted (NSM) FRP reinforcement systems, have gained widespread adoption for strengthening aging and deteriorated reinforced concrete (RC) structures. These systems have been shown to effectively enhance flexural, shear, and torsional capacities, while also providing confinement to deficient members. However, a key challenge identified in the literature is the bond behavior at the FRP–concrete interface, as premature debonding frequently governs failure and restricts the full utilization of the tensile capacity of FRP materials. Compared to externally bonded laminates, NSM FRP techniques offer improved force transfer mechanisms and reduced susceptibility to debonding, leading to enhanced structural performance and reliability [27].

Applications of FRP strengthening for concrete slabs, beams, and columns using FRP sheets are illustrated in Figure 2(a–c) [28]. Figure 2(d) presents examples of flexural strengthening of reinforced concrete beams using FRP plates, as well as column confinement achieved through FRP wrapping [66]. A notable application of FRP technology in metallic structures is demonstrated by the strengthening of the 120-year-old Münchenstein Railway Bridge in Switzerland, shown in Figure 2(e). This riveted steel bridge posed significant challenges for conventional strengthening approaches, as the uneven riveted surfaces rendered traditional steel plate strengthening and bonded CFRP plates impractical. To address these limitations, Ghafoori et al. [29] proposed an innovative fatigue-strengthening strategy incorporating unbonded prestressed CFRP plates combined with wireless structural health monitoring sensors. This approach enabled effective strengthening of fatigue-critical regions while facilitating long-term performance monitoring, as illustrated in Figure 2(f).

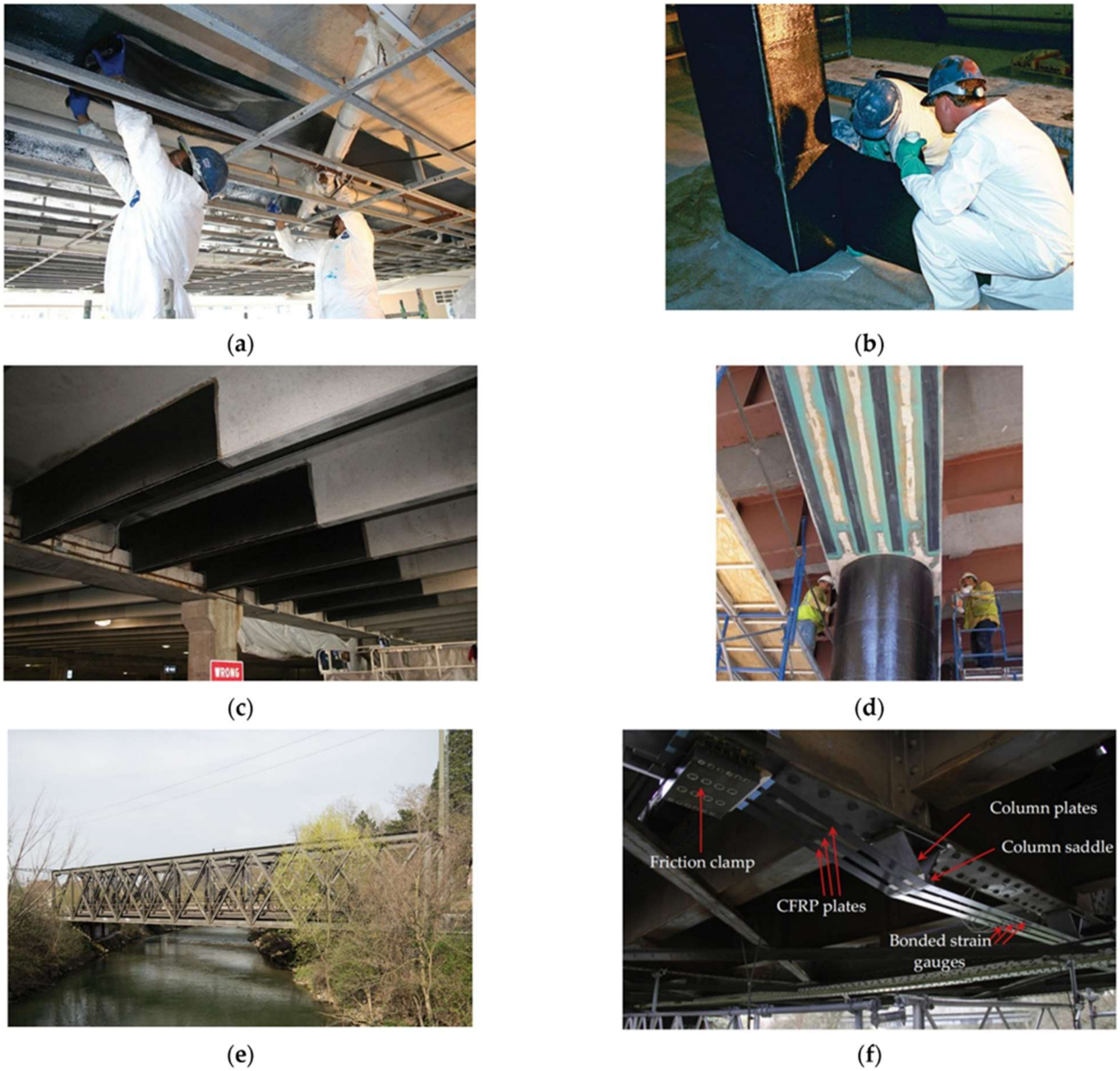


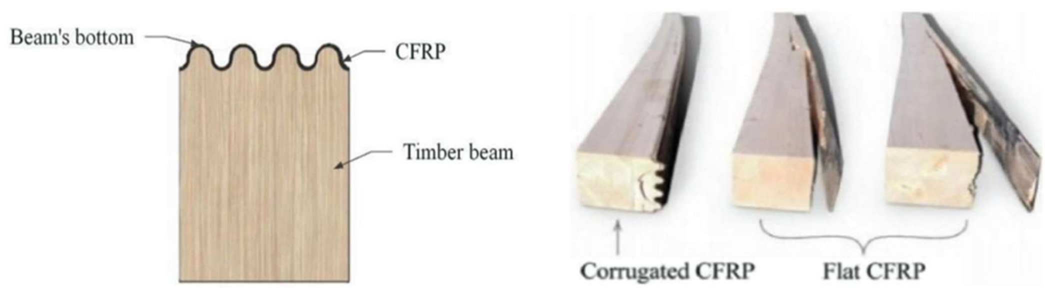
Figure 2. Applications of fiber-reinforced polymer (FRP) systems in structural strengthening: (a) flexural strengthening of reinforced concrete slabs using FRP sheets [28]; (b) confinement of reinforced concrete columns through FRP fabric wrapping [28]; (c) CFRP strengthening of reinforced concrete beams [28]; (d) flexural strengthening of beams using bonded FRP plates; (e) the 120-year-old Münchenstein Railway Bridge, Switzerland [29]; and (f) strengthening of the Münchenstein Bridge using prestressed unbonded CFRP plates integrated with wireless sensors for long-term prestress and structural performance monitoring [29].

2.2.1 Strengthening Timber Beams Using FRP Systems

Timber is increasingly used in structural applications due to its sustainability and favorable strength-to-weight characteristics; however, its inherent variability, low tensile strength, and limited stiffness often restrict its use in large-span or heavily loaded structures. Although engineered timber products partially address these limitations, fiber-reinforced polymer (FRP) systems provide an effective and practical means of further enhancing the structural performance of timber members. Consequently, FRP-reinforced timber beams have attracted growing research interest for both new construction and structural rehabilitation. FRP reinforcement can be incorporated into timber elements either during manufacturing by embedding reinforcement at critical locations or applied in situ using externally bonded reinforcement (EBR), prefabricated shells, or wet lay-up techniques [30]. The insertion of FRP into timber beams has been shown to increase load-bearing capacity and reduce the required cross-sectional dimensions in new construction [31]. In retrofit applications, FRP reinforcement can extend the span length of existing beams [32], and CFRP-based shear connectors have been successfully employed to enhance composite timber systems [33]. Improvements in elastic stiffness achieved through FRP reinforcement are particularly important for controlling deflections and meeting serviceability limit state requirements in large-span timber structures [12].

Bond performance between FRP and timber is a critical factor governing the effectiveness of strengthening systems. Epoxy resins are widely used due to their high chemical resistance and bond strength, while polyurethanes offer good wear resistance and toughness. In addition to load transfer, the resin matrix can serve as a protective layer for the timber substrate [34]. Bond strength is influenced by multiple factors, including timber species, surface geometry, boundary conditions, specimen configuration, and FRP dimensions [35]. Timber beams typically fail in tension or exhibit excessive deflection due to low stiffness, making serviceability a key design concern. Proper bonding techniques such as externally bonded reinforcement (EBR), horizontal or vertical near-surface mounting (HNSM and VNSM), and glued-in rods are essential for achieving composite action. Adhesive selection, surface preparation, and bond length significantly influence load transfer, failure mode, and overall structural response. While FRP-reinforced timber beams generally exhibit improved ductility compared to unreinforced members, durability considerations such as freeze–thaw exposure and environmental effects remain important research topics.

Fava et al. [36] investigated the effects of bond length, fiber orientation, and FRP type on the performance of FRP–wood joints, reporting that failure commonly occurred at the adhesive–FRP or adhesive–glulam interface. Compared to unreinforced timber, FRP-strengthened beams exhibited more ductile behavior, as opposed to brittle tensile failure [37]. Vessby et al. [38] examined bond lengths of 50, 150, and 250 mm and found that increasing bond length led to improved strength and stiffness of the reinforced section. Kramár et al. [39] investigated the influence of corrugated timber surfaces on FRP bonding performance, as illustrated in Figures 3. Four-point bending tests on unreinforced beams, wet-applied FRP-strengthened beams, and beams reinforced using vacuum-assisted resin transfer molding (VARTM) revealed that corrugated CFRP-reinforced beams achieved the highest bending resistance, attributed to enhanced mechanical interlocking at the FRP–timber interface.



(a) (b)

Figure 3 (a) Corrugated timber beam with FRP sheet laminated; (b) Failure modes in corrugated and flat beams with FRP sheets [39].

Numerous experimental studies have confirmed that the reinforcement ratio (number of FRP layers) is a key parameter governing the structural performance of FRP-strengthened timber beams. Yang et al. [40] tested six unreinforced timber beams and 21 CFRP- and GFRP-reinforced beams, reporting increases in ultimate capacity ranging from 17.7% to 77.3% for reinforcement ratios between 0.37% and 1.13%. Increased reinforcement ratios were also associated with changes in failure mode, as FRP sheets delayed or prevented brittle tensile failure, reduced the influence of natural wood defects, and enhanced stiffness and ductility. Adhesive selection, surface preparation, and bond length significantly influence load transfer, failure mode, and overall structural response. Overall, FRP strengthening has proven to be an effective strategy for enhancing the strength, stiffness, and reliability of timber beams.

2.2.2 Strengthening concrete structural elements with FRP Sheets

Strengthening existing reinforced concrete (RC) structural elements including beams, slabs, columns, bridge components, and prestressed members is an effective strategy for improving flexural and shear capacity, ductility, and strain control under diverse loading conditions [41] ,[42]. Fiber-reinforced polymer (FRP) systems are widely used for this purpose and are typically applied as externally bonded (EB) laminates or near-surface mounted (NSM) bars or strips, with or without adhesives and mechanical anchorage [42]. For RC columns subjected primarily to axial compression, FRP confinement is one of the most effective strengthening techniques. Wrapping EB-FRP sheets around the column perimeter restrains lateral expansion, delays concrete crushing, and enhances compressive strength and ductility [43], [44]. While partial wrapping provides limited confinement [45], full wrapping has been shown to significantly improve performance, with reported strength increases of up to 66% using a single CFRP layer and 123% with three layers [46]. EB-FRP confinement has demonstrated greater effectiveness under axial loading than NSM systems alone, although hybrid EB–NSM approaches offer the most efficient overall strengthening solution.

Although FRPs possess high tensile strength, their compressive strength is typically only 20–50% of their tensile capacity, making them susceptible to local buckling under compression [45], [47]. Consequently, circumferential fiber orientations, such as hoop or spiral wrapping, are preferred for column confinement [48]. Circular columns benefit from uniform confinement and stress distribution, whereas rectangular columns often require corner rounding to prevent stress concentration and premature FRP debonding [43]. FRP-confined columns generally exhibit enhanced ductility and energy dissipation capacity, particularly when hybrid FRP systems are employed [48]. Flexural strengthening of RC members is commonly achieved by externally bonding FRP sheets along the tension face of the member, with fibers aligned parallel to the longitudinal axis [49]. Near-surface mounted FRP strip systems have shown superior performance compared to EB laminates in flexural applications, with reported strength increases exceeding 200% due to improved stiffness and bond behavior [43], [49], [50]. In addition to increasing flexural capacity, FRP reinforcement reduces deflection and crack width, contributing to improved serviceability and ductility [51]. Hybrid FRP configurations, including carbon–glass systems, have also demonstrated substantial flexural enhancement, with reported strength gains exceeding 100% in some applications [52].

FRP strengthening has proven particularly effective for aging and deteriorated structures. Case studies of prestressed concrete girders strengthened with EB CFRP plates have reported increases of 10% in serviceability load and over 50% in ultimate strength, while combined GFRP–CFRP systems have achieved strength gains exceeding 100% [53]. Increasing FRP thickness and employing combined flexural shear strengthening strategies further enhance structural performance hening is closely tied to the failure mode of the system. Common failures include FRP debonding, FRP rupture, concrete crushing, and combined flexural or shear failure with steel yielding [52]. Examples of these failure modes are illustrated in Figure 4. Among these, interfacial debonding is the most prevalent and often governs ultimate capacity [54], [55]. Debonding typically occurs as concrete cover separation, intermediate crack-induced debonding, or end debonding due to high interfacial stresses, particularly when surface preparation is inadequate [56], [57]. Because debonding prevents full utilization of FRP tensile capacity and results in brittle behavior [58], mitigation strategies such as intermediate anchorage systems in EB applications [59] and increased embedment length in NSM systems [51] are commonly recommended.

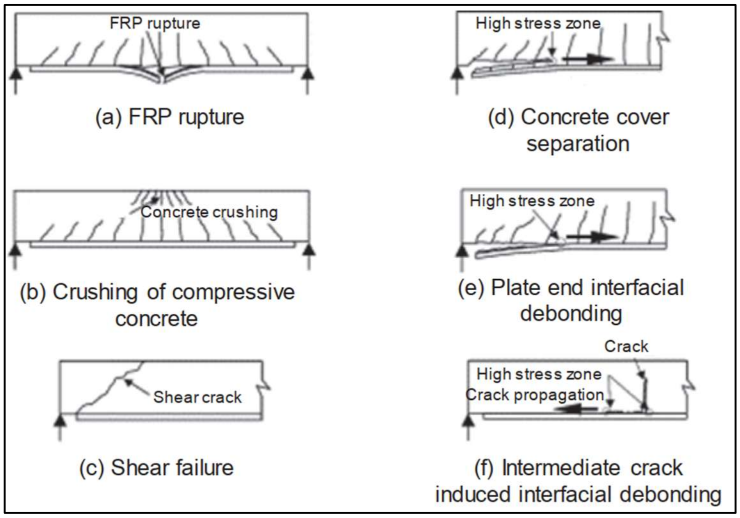


Figure 4. *Typical failure modes of FRP-strengthened structures* [55]

3. Educational Framework and Course Context

The instructional design of the composite retrofitting activity was grounded in outcomes-based education, experiential learning, and constructivist learning theory, with implementation supported through active learning and project-based learning (PBL) strategies. Collectively, these pedagogical approaches emphasize active student engagement, integration of theory with practice, and the development of higher-order cognitive and professional skills key objectives of contemporary engineering education and ABET accreditation criteria [60]. Experiential learning theory provides the primary conceptual foundation for the activity design. According to Kolb’s experiential learning model, effective learning occurs through a cyclical process involving concrete experience, reflective observation, abstract conceptualization, and active experimentation [61]. This framework has been widely adopted in engineering education to promote deeper conceptual understanding and to support students’ ability to transfer theoretical knowledge to real-world engineering contexts[62]. The hands-on nature of the FRP retrofitting activity directly engages students in this learning cycle by requiring them to design strengthening systems, fabricate composite materials, test structural performance, and reflect on observed behavior and failure modes.

Active learning principles further informed the instructional approach by shifting students from passive recipients of information to active participants in the learning process. Extensive research has demonstrated that active learning improves student performance, retention, and problem-solving ability In this study, active learning was operationalized through collaborative laboratory work, iterative design decisions, and structured reflection, enabling students to engage meaningfully with complex structural behavior and material interactions. Project-based learning extends these principles by situating learning within open-ended, authentic engineering tasks that mirror professional practice. PBL has been shown to enhance student motivation, teamwork, and design competence by requiring learners to address realistic constraints and evaluate multiple solution pathways [63]. This approach is particularly effective in structural engineering education, where performance-based behavior, constructability considerations, and material-dependent failure mechanisms are difficult to fully convey through lecture-based instruction alone. By engaging students in the full design–fabrication–testing–evaluation cycle, the FRP retrofitting activity reflects core PBL characteristics and encourages engineering judgment rather than procedural execution.

The educational framework was also informed by Bloom's revised taxonomy, which provides a structured approach to defining learning objectives and assessing cognitive development [64]. The activity was intentionally designed to move students beyond lower-order cognitive skills, such as remembering and understanding material properties, toward higher-order skills including analysis, evaluation, and creation. Students were required to justify design decisions, interpret experimental results, and assess the effectiveness of different strengthening strategies tasks aligned with the upper levels of Bloom's taxonomy [65]. Finally, constructivist learning theory underpins the integration of experiential and project-based elements within the activity. Constructivism posits that knowledge is actively constructed through inquiry, collaboration, and reflection rather than passively absorbed [66]. By working in teams, engaging with real materials, and confronting practical challenges such as bonding quality and delamination, students constructed their understanding of FRP retrofitting through direct experience and peer interaction. This approach supports the development of durable knowledge structures and professional competencies essential for structural engineering practice.

The educational framework was intentionally aligned with course learning objectives and ABET student outcomes. The activity was designed to support students' ability to (1) apply engineering principles to analyze structural behavior, (2) design strengthening solutions under realistic constraints, (3) conduct and interpret experiments, and (4) communicate technical findings effectively. These objectives align closely with ABET outcomes related to problem solving, design, experimentation, teamwork, and professional responsibility [60]. By incorporating composite fabrication and experimental testing, the activity also emphasized constructability and safety, which are critical yet often underrepresented components of structural engineering education. Students were required to follow laboratory safety protocols, properly handle epoxy and composite materials, and reflect on workmanship-related issues such as bonding quality and delamination. Prior studies have shown that integrating safety and constructability considerations into laboratory instruction enhances students' preparedness for professional practice [67].

4. Experimental Design/ Methodology

The activity was conducted across two cohorts of undergraduate students enrolled in the Structural Analysis course (CEGR 324) during separate academic offerings. Each cohort participated in the hands-on laboratory module as an integrated component of the course curriculum. The hands-on learning module began with an introductory lecture designed to establish the theoretical foundation for the experimental activities. The lecture introduced fiber-reinforced polymer (FRP) composites as retrofitting materials for structural systems and provided an overview of common strengthening techniques for structural members, as illustrated in Figure 5. Key motivations for structural retrofitting, including extending service life, enhancing load-carrying capacity, and improving structural safety, were discussed to place the laboratory work within a practical engineering context. Building on concepts introduced earlier in the course, selected case studies from the literature were used to illustrate both conventional and advanced retrofitting approaches, including steel jacketing, grout-based strengthening, and composite-based solutions using carbon fiber-reinforced polymer (CFRP), glass fiber-reinforced polymer (GFRP), and aramid fiber-reinforced polymer (AFRP) systems. These examples exposed students to the advantages, limitations, and constructability considerations associated with different strengthening methods.

Figure 5. *Presentation on FRP application in civil engineering*

Students worked in small collaborative groups, with an average of four students per group, to promote teamwork, peer learning, and shared responsibility during specimen preparation, FRP application, and experimental testing. The activity was delivered during the regular academic semester after coverage of fundamental structural analysis concepts, allowing students to apply analytical knowledge to observed structural behavior and design decisions. Following the preparatory instruction, the module was implemented as a design-focused laboratory experience. Brief discussions introduced FRP material behavior, strengthening mechanisms, and relevant design provisions (e.g., ACI 440), while most of the instructional time was devoted to hands-on work.

To broaden student exposure to composite retrofitting applications, each cohort focused on a different structural material system. One cohort strengthened scaled timber beams subjected to flexural loading, while the second cohort retrofitted concrete cylinders tested under axial compression. For each material system, control, partially wrapped, and fully wrapped configurations were evaluated. This dual-material framework was intended to highlight differences in structural response while reinforcing common principles related to bonding behavior, reinforcement continuity, and failure mechanisms.

In addition, an anonymous survey was administered after completion of the laboratory activities and testing observations to capture students' perceptions of their learning experience. A total of twenty-one students across the two course offerings completed the survey. The instrument included structured questions addressing prior familiarity with GFRP concepts, understanding of experimental results, perceived learning gains, and overall satisfaction. Open-ended questions asked students to identify the most valuable aspects of the activity, challenges encountered during specimen preparation and testing, knowledge or skills gained, perceived relevance to engineering practice, and suggestions for improvement.

Qualitative responses were analyzed using an inductive thematic approach. Similar responses were grouped into recurring categories, and the frequency of each theme was recorded to identify dominant patterns in student learning and experience. The combined use of artifact-based evaluation and survey feedback provided multiple forms of evidence to assess the educational impact of the hands-on composite retrofitting module.

4.1. Activity 1: FRP application to timber beams

This activity was designed to provide students with hands-on experience in the application of glass fiber-reinforced polymer (GFRP) sheets for strengthening timber beams subjected to flexural loading. Through direct involvement in specimen preparation, composite fabrication, curing, and testing, students gained practical insight into FRP-based retrofitting techniques, workmanship considerations, and the influence of strengthening configurations on structural performance.

Materials and Equipment

To ensure a safe and controlled laboratory environment, students were provided with appropriate personal protective equipment (PPE), including gloves, face masks, lab coats, and safety glasses. The materials and tools used in this activity included fiberglass cloth (GFRP sheets), polyester fiberglass resin, ketone catalyst, mixing containers, painting brushes, scissors or cutters, acetone for tool cleaning, and timber beam specimens. Flat working tables served as fabrication stations, and clamps were used to maintain the position of the GFRP wrapping during curing.

Specimen Preparation and Experimental Groups

Students were first introduced to the overall experimental plan through a live demonstration, as shown in Figure 5. Three categories of timber beam specimens were prepared for flexural testing: (1) Control specimens with no GFRP reinforcement; (2) Partially wrapped specimens, strengthened at the mid-span region; (3) Fully wrapped specimens, strengthened along the full effective span. Each group of students was assigned responsibility for preparing one type of specimen, allowing direct comparison of strengthening strategies and promoting collaborative learning.

Figure 6. *Demonstration of GFRP application to timber beams*

Uniform timber beams measuring 22 inches in length were selected and inspected to ensure clean, dry surfaces free of contaminants. Each beam was marked 2 inches from both ends, leaving an 18-inch effective span. This span was further divided into three equal segments of 6 inches, corresponding to the anticipated flexural demand regions during testing. These markings were transferred to all four sides of the beam to guide consistent GFRP placement, as illustrated in Figure 7.

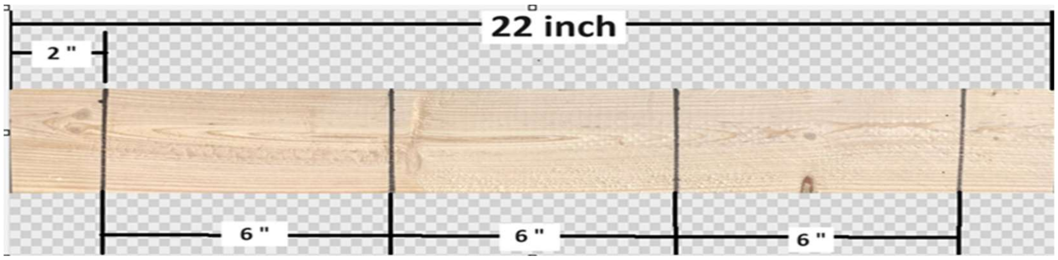


Figure 7. *Markings on a timber beam before GFRP lamination*

Partial GFRP Wrapping Procedure

For the partially strengthened specimens, students prepared a 12-inch-long, 6-inch-wide strip of fiberglass cloth. A resin mixture was produced by combining 50 mL of polyester resin with 2 mL of ketone catalyst and stirring thoroughly while minimizing air entrainment. A thin layer of the mixed resin was applied to the middle third (6-inch region) of the timber beam, as shown in Figure 8.

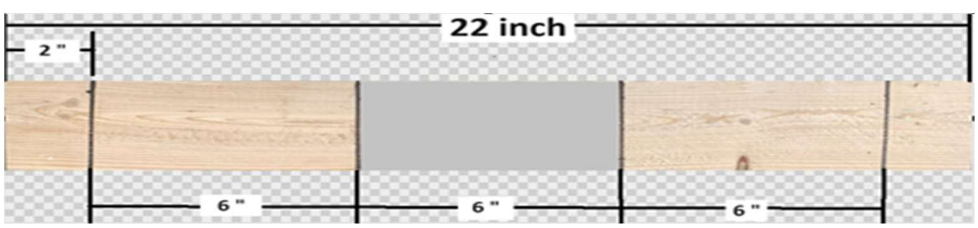


Figure 8. *Application of resin on the middle third of the span*

The fiberglass cloth was then placed onto the resin-coated surface and wrapped around the beam with a 2-inch overlap to ensure continuity. Additional resin was applied over the fiberglass to achieve full saturation, and brushes or rollers were used to remove trapped air bubbles. The wrapped region was subsequently covered with multiple layers of thin plastic film to maintain contact pressure and minimize resin loss during curing. Figure 9 shows students performing the partial wrapping process.

Figure 9. *Partial wrapping of GFRP on timber beams by students*

Full-Length GFRP Wrapping Procedure

For the fully strengthened specimens, students prepared a larger fiberglass cloth measuring 22 inches in length and 18 inches in width. A resin mixture consisting of 100 mL of polyester resin and 4 mL of ketone catalyst was prepared following the same mixing protocol. The resin was applied along the full 18-inch effective span of the beam, and the fiberglass cloth was wrapped around all sides of the timber member. To enhance strengthening effectiveness, a second layer of fiberglass cloth was applied with a 2-inch overlap. Each layer was fully saturated with resin, and care was taken to eliminate air voids between layers. The finished specimen was inspected for uniformity, fiber alignment, and bonding quality before being wrapped with thin plastic film to maintain consolidation during curing. Figures 10 illustrate the full-length GFRP application performed by students.

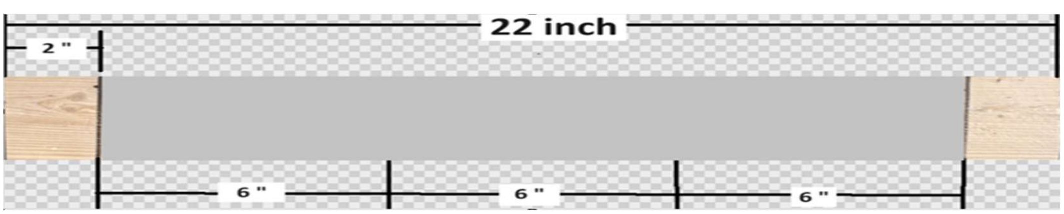


Figure 10*. Full length wrapped timber.*

Curing Process

After fabrication, all strengthened specimens were clamped to ensure the GFRP remained in the intended position during curing. The specimens were cured in an open laboratory environment for a period of seven days. Upon completion of the curing period, the clamps and plastic wrapping were removed, and the specimens were prepared for mechanical testing.

Flexural Strength Testing

Flexural strength testing was conducted in accordance with ASTM C78 [32] using a third-point loading configuration. Beam specimens with dimensions of 534 × 152 × 152 mm were loaded continuously without shock using a Universal Testing Machine (UTM). A loading rate of 0.9 MPa/min was applied until failure occurred. Figure 10 shows a partially wrapped timber beam undergoing flexural testing.

Figure 11. *Flexural strength test on a partially wrapped timber beam.*

The flexural strength was calculated using Equation (1):

$$f=PL/bd^2 \qquad (1)$$

where,

f = Flexure strength (psi)

P = maximum load indicated by the UTM (lb)

L = span length of beam (in)

b = width of beam (in)

d = depth of beam (in)

Students recorded load–displacement behavior, observed crack initiation and propagation, and documented failure modes for each specimen. These observations formed the basis for subsequent comparison of unstrengthen, partially wrapped, and fully wrapped beams, reinforcing the relationship between strengthening configuration, material behavior, and structural performance.

Activity 2: FRP application to concrete cylinders

This activity was designed to provide undergraduate students with hands-on experience in the application of glass fiber-reinforced polymer (GFRP) systems for strengthening concrete elements subjected to axial compression. Building upon earlier course modules that introduced concrete mix design, casting, and curing, this experiment enabled students to investigate the influence of external FRP confinement on the mechanical performance and failure behavior of cured concrete cylinders. Through controlled fabrication and testing, students developed practical insight into the role of composite materials in enhancing the structural integrity, strength, and ductility of concrete structural elements.

Materials and Equipment

Students were provided with appropriate personal protective equipment (PPE), including gloves, face masks, lab coats, and safety glasses. The materials and equipment used in this activity included string and duct tape for temporary confinement, brushes and rollers for adhesive application, fiberglass wrapping strips (3-inch and 8-inch widths), and a two-part epoxy adhesive (PC-Concrete Repair and Anchoring Epoxy, Parts A and B). Concrete materials included Type I ordinary Portland cement, fine aggregate (sand), coarse aggregate (gravel), water, tamping rods, trowels, shovels, concrete mixing trays, and plastic cylindrical molds.

Concrete Specimen Preparation

Concrete cylinders were prepared in accordance with ASTM standards to ensure consistency and reliability of test results. Type I ordinary Portland cement conforming to ASTM C150 specifications was used [52]. Locally sourced fine and coarse aggregates were employed, with fine aggregate having a specific gravity of 2.64, water absorption of 0.7%, and fineness modulus of 2.80. The coarse aggregate was well graded, with a maximum nominal size of 19 mm, specific gravity of 2.68, water absorption of 0.5%, and unit weight of 1602 kg/m^3. The concrete mix proportions are summarized in Table 1.

Table 1. Concrete mix proportion

Material	Quantity	Unit
Cement	15.4	lb
Sand	31.5	lb
Coarse Aggregate	50	lb
Water	8.8	lb

Mixing was performed following ASTM C192 procedures. Cement, sand, and coarse aggregate were first dry-mixed for approximately two minutes to ensure uniform distribution. Water was then added gradually while mixing continued for an additional three to four minutes until a homogeneous and workable mixture was achieved.

Specimen Casting and Curing

Plastic cylindrical molds measuring 4 inches in diameter and 8 inches in height were placed on a firm, level surface prior to casting. Each mold was filled in three equal layers, with each layer compacted using a tamping rod applied 25 times in a uniform radial pattern. The sides of the molds were lightly tapped with a rubber hammer to eliminate entrapped air. Student participation during casting is shown in Figure 12. After consolidation, the specimen surfaces were leveled flush with the top of the mold using a straightedge, and excess concrete was removed. Mold lids were securely placed to minimize moisture loss, and each specimen was clearly labeled. The filled molds were stored in a controlled humid environment for an initial curing period of 24 hours. Following demolding, the concrete cylinders were submerged in a water tank for a 28-day curing period to ensure full hydration and strength development.

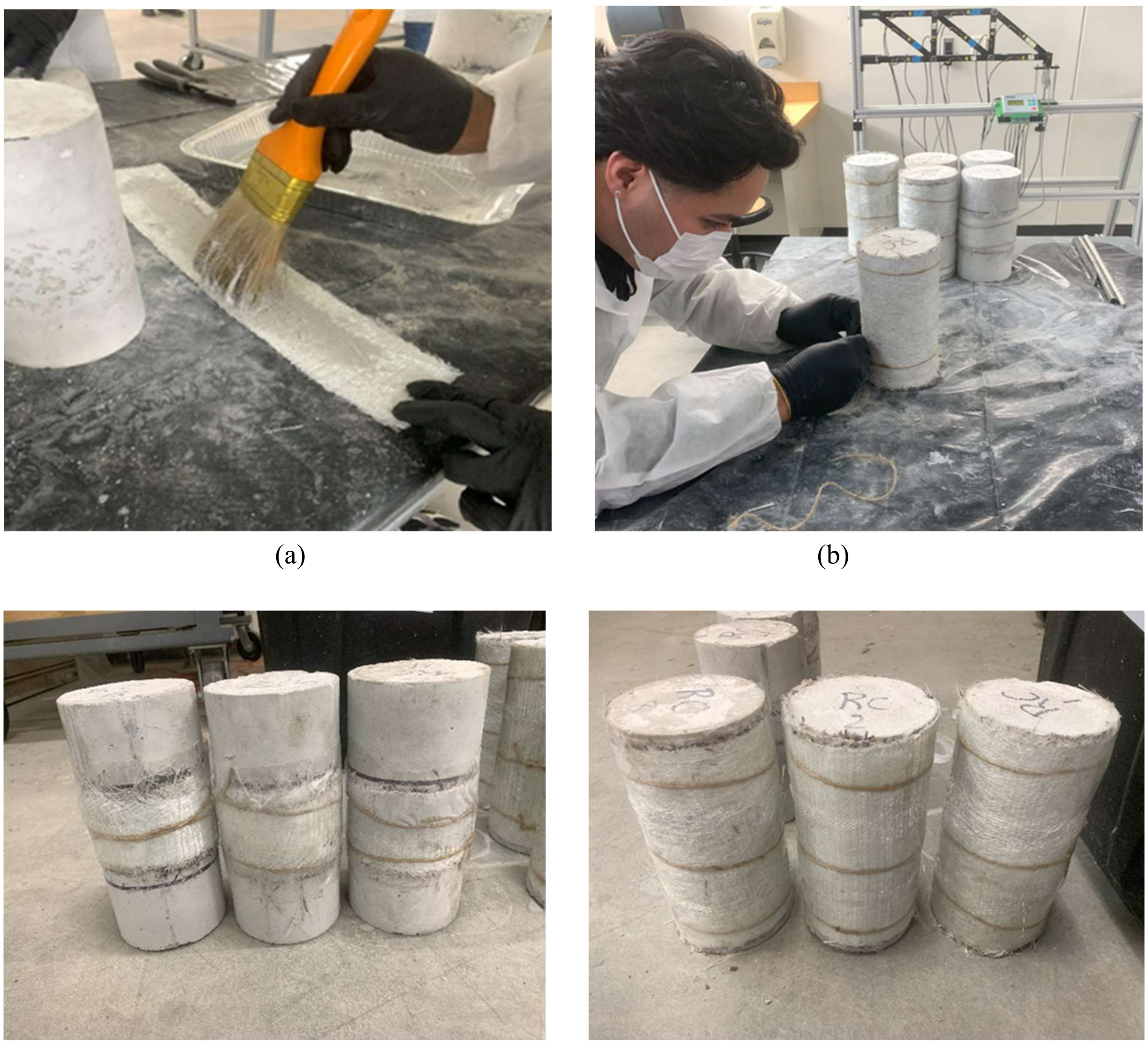
Figure 12. *Casting of concrete cylinders by student groups.*

GFRP Application Procedures

Prior to FRP application, all cured concrete cylinders underwent thorough surface preparation to promote effective bonding. Dust, debris, and surface contaminants were removed, and the concrete surface was mechanically roughened to create a uniform texture, as shown in Figure 13. This step was essential for enhancing adhesive penetration and interfacial bond strength. The GFRP application was conducted using three specimen configurations: (1) unwrapped control specimens, (2) partially wrapped specimens confined over a central portion of the cylinder height, and (3) fully wrapped specimens confined along the entire cylinder height. This grouping enabled students to evaluate the effect of confinement extent on compressive behavior.

Figure 13*. Surface preparation before GFRP application*

A uniform layer of epoxy adhesive was applied to the concrete surface using brushes and rollers (Figure 14a). The GFRP sheets were then wrapped circumferentially around the cylinder with adequate overlap to ensure continuity. Care was taken to maintain consistent fiber orientation and to eliminate air voids during lamination. Following wrapping, the specimens were left to cure under ambient laboratory conditions for 28 days to allow full adhesive hardening and bond development. Representative wrapped specimens are shown in Figures 14 b-c.



(a) (b) (c) (d)

Figure 14: *(a) Application of epoxy resin on GFRP; (b) Full-length GFRP wrapping of concrete cylinder; (c) GFRP-wrapped concrete cylinders, partially wrapped; (d) Full-length wrapped*

Compression Strength Testing

Axial compression testing was conducted in accordance with ASTM C39/C39M [30] using a Universal Testing Machine (Instron 1000HDX-C3-G7B) at the Materials Laboratory, Morgan State University. Each cylinder was centered carefully to ensure uniform load application. Load was applied monotonically until failure occurred. The compressive strength was calculated directly by the testing machine as the ratio of maximum applied load to the cross-sectional area of the cylinder. For each configuration, the reported compressive strength represents the average value obtained from multiple specimens. Test results and observed failure modes are presented and discussed in the following section.

Student learning was assessed through qualitative analysis of laboratory reports submitted at the completion of the activity. Reports were evaluated for evidence of conceptual understanding, design reasoning, experimental interpretation, and professional practice. This artifact-based assessment approach is commonly used in engineering education to evaluate learning outcomes in design-oriented laboratory courses.

5. Results and Discussion

This section presents the educational outcomes of the hands-on FRP retrofitting module, based on analysis of student laboratory reports and post-activity survey responses. The results focus on evidence of conceptual understanding, practical skill development, and student perceptions of the learning experience. Observed structural performance trends and failure behavior are discussed only as context to illustrate how experimental observations supported student learning. The combined results provide insight into the effectiveness of integrating composite retrofitting into undergraduate structural engineering education.

5.1 Assessment of Student Learning Through Group Laboratory Reports

Student learning outcomes were assessed through qualitative analysis of group laboratory reports submitted upon completion of the hands-on FRP retrofitting activities. Each student group documented the design rationale, specimen preparation procedures, experimental results, and interpretation of structural behavior for either timber beam strengthening under flexural loading or concrete cylinder confinement under axial compression. This artifact-based assessment approach provided direct evidence of student learning in a design-oriented laboratory setting. Analysis of the reports indicated that students developed a strong conceptual understanding of FRP strengthening mechanisms across different structural materials. Groups consistently articulated the role of GFRP in enhancing tensile capacity and stiffness in timber beams and in providing lateral confinement to improve compressive strength and ductility in concrete cylinders.

Students demonstrated the ability to distinguish between the structural behavior of unstrengthened control specimens and those strengthened using partial and full wrapping configurations, reflecting meaningful engagement with material behavior and load transfer principles.

The design justification sections of the reports revealed growth in performance-based design thinking. Student groups critically evaluated the effectiveness of partial versus full GFRP wrapping by comparing observed load capacity, deformation behavior, and failure modes. Many reports acknowledged the trade-offs between structural performance and constructability, noting that while full wrapping generally provided superior strength and ductility, partial wrapping offered localized improvements with reduced material usage and fabrication effort. This comparative reasoning reflects the development of informed engineering judgment beyond prescriptive design approaches.

Experimental interpretation and failure mode analysis further demonstrated higher-order cognitive engagement. Groups accurately identified governing failure mechanisms, including tensile rupture of timber fibers, FRP debonding, fiber rupture, and concrete crushing. Students frequently linked premature failures or reduced performance to practical factors such as inadequate surface preparation, non-uniform resin application, or air entrapment beneath the GFRP layers. These observations indicate that students not only understood theoretical strengthening concepts but also recognized the critical role of workmanship and bonding quality in real-world FRP applications. The group-based nature of the reports also highlighted the development of professional and collaborative skills. Reports documented coordinated task allocation during specimen preparation, adherence to laboratory safety protocols, and collective interpretation of experimental results. The clarity and technical depth of the written reports suggest improved communication skills and an increased ability to synthesize experimental observations into coherent engineering conclusions.

Overall, the laboratory report analysis indicates that the hands-on FRP retrofitting activities effectively supported course learning objectives related to structural behavior, materials engineering, experimental reasoning, and design decision-making. The findings demonstrate that embedding composite retrofitting within a collaborative, design-focused laboratory environment can promote deep learning and better prepare undergraduate students for contemporary structural engineering practice involving advanced materials and infrastructure rehabilitation.

5.2. Student Perceptions and Learning Experience Based on Post-Activity Survey

To complement the artifact-based evaluation presented in Section 5.1, student perceptions of the learning experience were collected through a post-activity survey administered after completion of the laboratory module. A total of 21 students across the two course offerings responded. The survey included structured items and open-ended questions designed to assess prior familiarity with FRP strengthening perceived learning gains, overall satisfaction, and reflections on the most valuable aspects and challenges of the hands-on activity. Qualitative responses were analyzed using an inductive thematic approach, and the frequency of recurring themes was used to identify dominant patterns in student experience. Survey responses indicated that most students entered the activity with limited prior exposure to FRP strengthening concepts, suggesting that the module introduced new material rather than reinforcing previously developed knowledge.

Analysis of open-ended responses revealed that real-world relevance was the most frequently reported outcome, mentioned by 18 students (86%). Students emphasized the importance of understanding how FRP systems are used in strengthening and rehabilitating existing structures and recognized the practical value of learning modern composite retrofit techniques. Hands-on engagement was identified as another dominant theme, reported by 16 students (76%). Students noted that working directly with the materials helped them better understand the application process and provided a clearer connection between classroom concepts and structural behavior. One student commented, "Seeing how the wrapping actually affected the strength made the concept much clearer than just learning it in class." Twelve students (57%) emphasized the value of observing structural response during testing. These responses indicated that seeing crack development, load capacity differences, and failure behavior helped students relate theoretical expectations to actual performance. In addition, eleven students (52%) specifically referenced an improved understanding of performance differences among control, partially wrapped, and fully wrapped specimens, particularly the magnitude of strength gains associated with continuous reinforcement. Awareness of constructability and workmanship considerations was mentioned by eight students (38%). These responses focused on practical challenges such as surface preparation, resin application, fiber alignment, and bonding quality. This theme indicates that the activity increased student understanding of implementation factors that influence the effectiveness of FRP systems in practice.

The distribution of the dominant learning themes identified from student responses is presented in Figure 15. The results show that the primary impact of the activity was not only conceptual understanding, but also increased awareness of real-world application, practical implementation, and the relationship between design decisions and structural performance.

Overall satisfaction with the activity was high, with the majority of students rating the experience between 8 and 10 on a 10-point scale. Collectively, the survey results indicate that the hands-on FRP module was effective in introducing new technical content, strengthening the connection between theory and practice, and increasing student engagement with structural rehabilitation concepts.

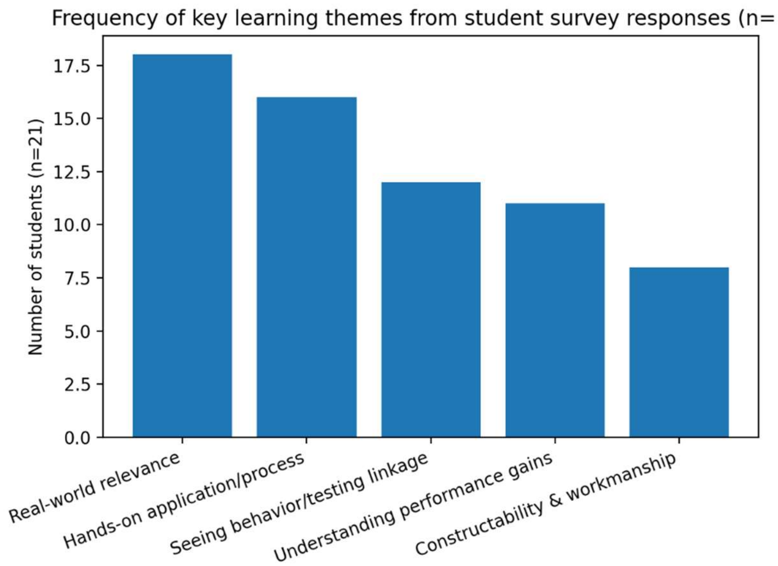


Figure 15: *Frequency of key learning themes identified from student survey responses (n = 21).*

5.3. Structural Performance of FRP-Strengthened Timber Beams

Flexural testing of the timber beams revealed clear and consistent performance differences among the three specimen configurations: unstrengthen control beams, partially wrapped GFRP beams, and fully wrapped GFRP beams. The control specimens exhibited brittle tensile failure at the bottom fibers, reflecting the inherently low tensile strength and stiffness of timber. Failure typically occurred suddenly and was initiated at natural material discontinuities such as knots or grain irregularities, consistent with expected behavior of unreinforced timber members under flexural loading. The experimental results, illustrated in Figure 16, demonstrate a consistent increase in flexural strength when GFRP wrapping is applied, either partially or fully.

Partially wrapped GFRP beams demonstrated measurable improvements in flexural capacity and stiffness compared to the control specimens. The application of GFRP reinforcement over the central third of the span delayed crack initiation and reduced crack propagation within the tensile zone, indicating that localized strengthening can enhance performance in critical regions. However, the effectiveness of partial wrapping varied across groups. Relative to the control beams, flexural strength increased by 0.57%, 16.72%, and 34.23% for Groups G1, G2, and G3, respectively. The negligible improvement observed in

Group G1 suggests that the performance of partial wrapping is highly sensitive to application quality and bonding conditions. Potential contributing factors include inadequate adhesion between the GFRP and timber surface, insufficient overlap of the GFRP layers, or premature debonding that limited effective stress transfer. These results highlight the susceptibility of discontinuous reinforcement configurations to localized stress concentrations at wrap terminations.

Fully wrapped GFRP beams exhibited the most significant enhancement in structural performance. Compared to both control and partially wrapped specimens, fully wrapped beams demonstrated higher ultimate load capacity, reduced midspan deflection, and improved ductility. Failure in these specimens was generally more gradual and was characterized by progressive GFRP debonding or fiber rupture rather than abrupt tensile fracture of the timber substrate. These observations align with existing literature, which indicates that continuous FRP confinement promotes more uniform stress redistribution and suppresses brittle failure mechanisms in timber members [27],[28]. Quantitatively, full-length GFRP wrapping increased flexural strength by 18.63%, 53.93%, and 54.92% for Groups G1, G2, and G3, respectively, relative to the control beams. The substantially higher strength gains observed in Groups G2 and G3 underscore the effectiveness of continuous reinforcement. Full-length wrapping likely enhanced load distribution by providing uniform stress transfer along the entire beam length, minimizing localized stress concentrations and reducing the likelihood of premature debonding. Additionally, the confinement effect of the continuous GFRP jacket restrained crack development, contributing to improved load-bearing capacity and overall structural integrity.

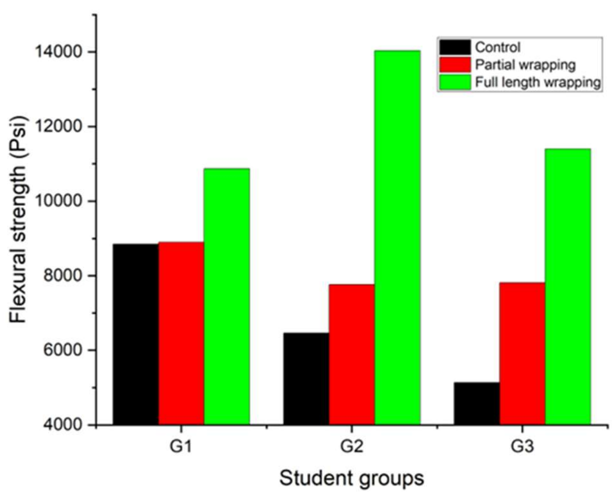


Figure 16*. Flexural strength of timber beams for three groups*

Overall, the results demonstrate that GFRP wrapping is an effective technique for strengthening timber beams, with performance strongly dependent on reinforcement configuration, bonding quality, and application consistency. While partial wrapping can provide localized improvements, full-length wrapping offers superior and more reliable enhancement of flexural performance. Future improvements should focus on optimizing surface preparation, adhesive application, and overlap detailing to further improve bond performance and mitigate premature failure. From an educational standpoint, the clear contrast in behavior among the three configurations enabled students to directly correlate reinforcement layout with structural response. The activity reinforced fundamental concepts related to flexural behavior, strain compatibility, and failure mechanisms, while also highlighting the practical importance of constructability and workmanship in composite retrofitting applications.

5.4 Compressive Behavior of FRP-Confined Concrete Cylinders

Compression testing of the concrete cylinders demonstrated the effectiveness of GFRP wrapping in enhancing compressive strength and deformation capacity. Clear performance distinctions were observed among the three specimen configurations: unwrapped control cylinders, partially wrapped GFRP cylinders, and fully wrapped GFRP cylinders. As illustrated in Figure 17, the application of GFRP laminates resulted in measurable strength gains, with the highest improvements consistently observed in fully wrapped specimens.

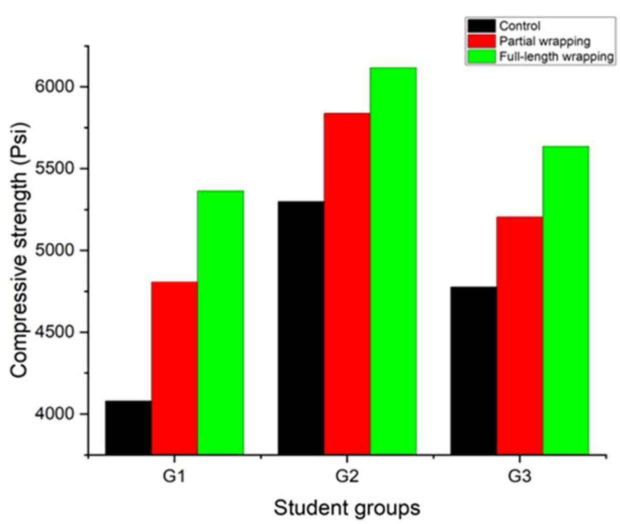
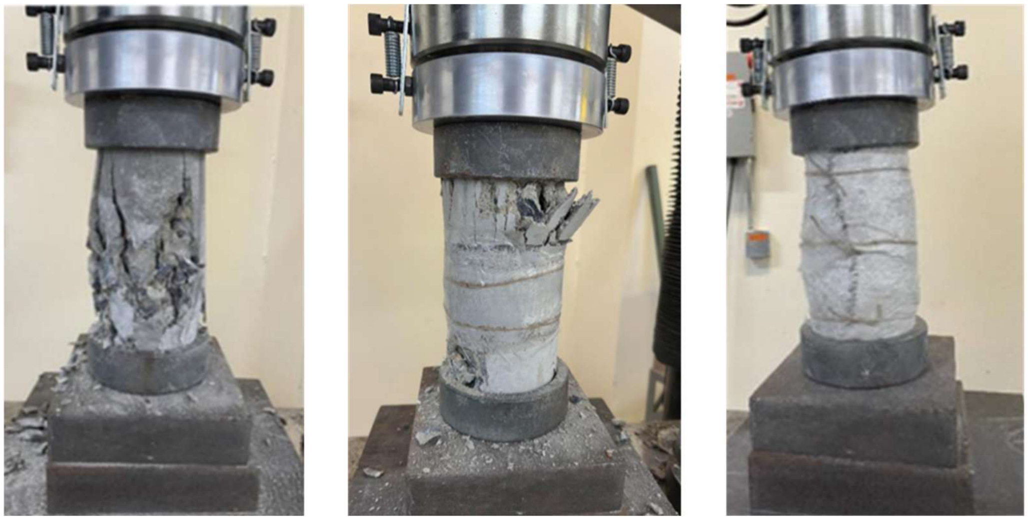


Figure 17. *Compression strength of concrete cylinders for three groups*

Unwrapped control cylinders failed in a brittle manner characterized by vertical cracking and concrete crushing, accompanied by limited post-peak deformation. This behavior is typical of unconfined concrete under axial compression and served as a baseline for evaluating the effectiveness of GFRP confinement. Partially wrapped cylinders exhibited moderate yet consistent improvements in compressive strength relative to the control specimens. Strength increases of 17.84%, 10.15%, and 8.93% were recorded for Groups G1, G2, and G3, respectively. The localized GFRP confinement in the central region of the cylinders delayed crack initiation and restrained lateral expansion within the wrapped zone. However, failure often initiated in the unconfined regions, indicating that discontinuous confinement limits the overall effectiveness of the strengthening system. These results highlight the sensitivity of compressive performance to the extent and continuity of FRP confinement.

Fully wrapped GFRP cylinders demonstrated the most significant enhancement in compressive behavior. Compared to the control specimens, compressive strength increased by 31.50%, 15.42%, and 17.95% for Groups G1, G2, and G3, respectively. In addition to higher peak strength, fully wrapped specimens exhibited improved strain capacity and a more ductile failure response. Failure typically occurred through progressive rupture of the GFRP jacket following substantial lateral dilation of the concrete core, consistent with confinement-based strengthening mechanisms reported in prior studies [32,36]. The continuous GFRP jacket provided uniform confinement pressure, effectively delaying concrete crushing and enhancing load-bearing capacity.

Overall, the results confirm that GFRP wrapping is an effective technique for improving the compressive performance of concrete elements. While partial wrapping can provide meaningful strength enhancement where full confinement is impractical, full-length wrapping offers superior and more reliable improvements in strength and ductility. The observed failure patterns, summarized in Figure 18, further illustrate the role of confinement continuity in governing structural response. From an educational perspective, the comparative behavior of unwrapped, partially wrapped, and fully wrapped cylinders reinforced key theoretical concepts related to confinement pressure, hoop stress development, and stress–strain enhancement in FRP-confined concrete. By directly observing failure modes and deformation behavior during testing, students were able to connect abstract analytical models with physical structural response, deepening their understanding of composite retrofitting principles in compression-dominated systems.



(a) ***(b)*** ***(c)***

Figure 18. *(a)Failure pattern of concrete cylinders for control specimen, (b)partially wrapped specimen, (c) full-length wrapped cylinder*

5.5 Comparison of Strengthening Mechanisms Across Material Systems

A key outcome of the dual-material approach was the opportunity for students to compare FRP strengthening mechanisms in timber and concrete systems. While FRP reinforcement in timber primarily enhanced tensile capacity and stiffness under flexural loading, FRP confinement in concrete predominantly improved compressive strength and ductility by restraining lateral expansion. Despite these differences, common principles emerged across both activities, including the importance of surface preparation, fiber orientation, bond quality, and curing conditions. Students observed that inadequate bonding or improper fiber placement could significantly reduce strengthening effectiveness, reinforcing the practical challenges associated with field implementation of FRP systems. This comparative framework strengthened students' understanding of material-specific behavior while emphasizing the versatility of FRP composites as a retrofitting solution across multiple structural materials.

6. Conclusion

This paper presented a hands-on, design-oriented learning initiative that integrates fiber-reinforced polymer (FRP) composite retrofitting into undergraduate structural engineering education. Through the fabrication, strengthening, and testing of scaled timber beams and concrete cylinders, students were actively engaged in the full design–fabrication–testing cycle, enabling them to connect theoretical concepts with real-world structural behavior and constructability considerations. Experimental results demonstrated that FRP retrofitting significantly enhances structural performance across both material systems. For timber beams subjected to flexural loading, glass fiber-reinforced polymer (GFRP) wrapping improved strength, stiffness, and ductility, with full-length wrapping providing the most consistent and substantial performance gains. In concrete cylinders tested under axial compression, GFRP confinement increased compressive strength and deformation capacity, with fully wrapped specimens exhibiting superior performance compared to partially wrapped and unwrapped controls. Across both experiments, observed failure modes highlighted the critical role of bonding quality, reinforcement continuity, and workmanship in achieving effective strengthening.

From an educational perspective, analysis of group laboratory reports provided direct evidence that the hands-on activities supported key learning objectives related to structural behavior, composite material performance, experimental interpretation, and engineering design judgment. Students demonstrated an improved ability to evaluate strengthening strategies, interpret failure mechanisms, and consider constructability and material limitations competencies that are difficult to cultivate through lecture-based instruction alone. The collaborative, design-focused nature of the activities also fostered professional skills such as teamwork, technical communication, and adherence to laboratory safety practices, aligning with ABET student outcomes and contemporary engineering education goals.

Overall, the findings indicate that embedding FRP retrofitting within structural design coursework is an effective approach for bridging the gap between theory and practice. By exposing students to advanced materials and modern rehabilitation techniques, the initiative enhances student preparedness for professional practice in infrastructure rehabilitation, sustainability, and resilience-oriented design.

Future Work

Future implementations of this learning module will focus on expanding both the technical and educational scope of the activity. From a technical standpoint, additional variables such as fiber orientation, multiple FRP layers, alternative resin systems, and different strengthening configurations will be explored to provide students with a broader understanding of composite behavior and design optimization. Extending the experiments to include full-scale specimens or structural elements subjected to combined loading conditions may further enhance realism and learning depth.

From an educational assessment perspective, future offerings will incorporate structured pre- and post-activity surveys and rubric-based evaluations to quantitatively measure learning gains and capture individual student perspectives. Longitudinal studies examining the retention of knowledge and transfer of skills to subsequent courses or design projects are also planned. Additionally, the module may be adapted for graduate-level coursework or interdisciplinary settings to explore more advanced design standards and performance-based retrofitting approaches. By continuing to refine and expand this experiential learning framework, future work aims to further integrate advanced composite materials into civil and structural engineering curricula and to contribute to the ongoing modernization of engineering education.

7. REFERENCES

[1] W. Bi *et al.*, “Effects of chemical modification and nanotechnology on wood properties,” *Nanotechnol. Rev.*, vol. 10, no. 1, pp. 978–1008, Aug. 2021, doi: 10.1515/ntrev-2021-0065.

[2] S. Al-deen, G. Ranzi, and Z. Vrcelj, “Full-scale long-term and ultimate experiments of simply-supported composite beams with steel deck,” *J. Constr. Steel Res.*, vol. 67, no. 10, pp. 1658–1676, Oct. 2011, doi: 10.1016/j.jcsr.2011.04.010.

[3] J. Jiang, P. Li, and N. Nisticò, “Local and global prediction on stress-strain behavior of FRP-confined square concrete sections,” *Compos. Struct.*, vol. 226, p. 111205, Oct. 2019, doi: 10.1016/j.compstruct.2019.111205.

[4] P. de la Rosa García, A. Cobo Escamilla, and M. N. González García, “Analysis of the flexural stiffness of timber beams reinforced with carbon and basalt composite materials,” *Compos. Part B Eng.*, vol. 86, pp. 152–159, Feb. 2016, doi: 10.1016/j.compositesb.2015.10.003.

[5] H. Xiong, Y. Liu, Y. Yao, and B. Li, “Experimental Study on the Lateral Resistance of Reinforced Glued-Laminated Timber Post and Beam Structures,” *J. Asian Archit. Build. Eng.*, vol. 16, no. 2, pp. 379–385, May 2017, doi: 10.3130/jaabe.16.379.

[6] D. M. Franco Duran, “Developing Context and Practice-Based Curricula in Construction Engineering and Management,” in *Construction Research Congress 2022*, Reston, VA: American Society of Civil Engineers, Mar. 2022, pp. 10–20. doi: 10.1061/9780784483985.002.

[7] J. Zhou, Q. Zeng, and D. Huang, “Exploration and Research on the Project-Driven Teaching Mode of Building Materials and Testing Experimental Course,” *Educ. Reform Dev.*, vol. 6, no. 4, pp. 13–18, May 2024, doi: 10.26689/erd.v6i4.6803.

[8] O. Owolabi *et al.*, “Hands-on Learning Pedagogy in Teaching Concepts Relevant in the Analysis, Design, and Maintenance of Transportation Infrastructure Systems,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2678, no. 11, pp. 501–515, Nov. 2024, doi: 10.1177/03611981241242067.

[9] B. G. Famewo, P. O. Abiodun, G. B. Oguntimein, and O. A. Owolabi, “Impact of an Experimental Centric Learning on Peer Learning and Collaboration among Environmental Engineering Undergraduates in a Historical Black College and University,” *ASEE Annu. Conf. Expo. Conf. Proc.*, 2024, doi: 10.18260/1-2--47553.

[10] P. S. Perumal, K. Manoharan, and A. Pandian, “Crafting real-world learning: Industry-driven pedagogy for civil engineering education,” in *Pedagogical Revelations and Emerging Trends*, London: CRC Press, 2024, pp. 190–195. doi: 10.1201/9781003587538-37.

[11] C. Pöhler, E. V. Bachtiar, L. Yan, and B. Kasal, “Composites for structural strengthening, repair, rehabilitation, and retrofit,” in *Composite Materials*, Elsevier, 2021, pp. 205–226. doi:

10.1016/B978-0-12-820512-9.00005-8.

[12] Y. J. Kim, M. Hossain, and K. A. Harries, “CFRP strengthening of timber beams recovered from a 32year old quonset: Element and system level tests,” *Eng. Struct.*, vol. 57, pp. 213–221, Dec. 2013, doi: 10.1016/j.engstruct.2013.09.028.

[13] I. R. Kliger, R. Haghani, M. Brunner, A. M. Harte, and K.-U. Schober, “Wood-based beams strengthened with FRP laminates: improved performance with pre-stressed systems,” *Eur. J. Wood Wood Prod.*, vol. 74, no. 3, pp. 319–330, May 2016, doi: 10.1007/s00107-015-0970-5.

[14] K. Neale, “FRPs for structural rehabilitation: a survey of recent progress,” *Prog. Struct. Eng. Mater.*, vol. 2, no. 2, pp. 133–138, Apr. 2000, doi: 10.1002/1528-2716(200004/06)2:2<133::AID-PSE16>3.0.CO;2-C.

[15] X. Meng, D. Zhang, P. Feng, and N. Hu, “Review on mechanical behavior of solar cells for building integrated photovoltaics,” *Sustain. Struct.*, vol. 1, no. 2, 2021, doi: 10.54113/j.sust.2021.000009.

[16] H. Liu, X. Yang, X. Zhang, Q. Su, F. Zhang, and B. Fei, “The tensile shear bonding property of flattened bamboo sheet.,” 2021.

[17] J. R. Correia, “Fibre-Reinforced Polymer (FRP) Composites,” in *Materials for Construction and Civil Engineering*, Cham: Springer International Publishing, 2015, pp. 501–556. doi: 10.1007/978-3-319-08236-3_11.

[18] H. T. Ali *et al.*, “Fiber reinforced polymer composites in bridge industry,” *Structures*, vol. 30, pp. 774–785, Apr. 2021, doi: 10.1016/j.istruc.2020.12.092.

[19] J. R. Duflou, Y. Deng, K. Van Acker, and W. Dewulf, “Do fiber-reinforced polymer composites provide environmentally benign alternatives? A life-cycle-assessment-based study,” *MRS Bull.*, vol. 37, no. 4, pp. 374–382, Apr. 2012, doi: 10.1557/mrs.2012.33.

[20] J. Qureshi, “A Review of Fibre Reinforced Polymer Structures,” *Fibers*, vol. 10, no. 3, p. 27, Mar. 2022, doi: 10.3390/fib10030027.

[21] A. Vedernikov, A. Safonov, F. Tucci, P. Carlone, and I. Akhatov, “Pultruded materials and structures: A review,” *J. Compos. Mater.*, vol. 54, no. 26, pp. 4081–4117, Nov. 2020, doi: 10.1177/0021998320922894.

[22] T. Keller, N. A. Theodorou, A. P. Vassilopoulos, and J. de Castro, “Effect of Natural Weathering on Durability of Pultruded Glass Fiber–Reinforced Bridge and Building Structures,” *J. Compos. Constr.*, vol. 20, no. 1, Feb. 2016, doi: 10.1061/(ASCE)CC.1943-5614.0000589.

[23] M. Elkafrawy *et al.*, “GFRP-Reinforced Concrete Columns: State-of-the-Art, Behavior, and Research Needs,” *Buildings*, vol. 14, no. 10, p. 3131, Sep. 2024, doi: 10.3390/buildings14103131.

[24] H. N. Shiferaw and T. Kanakubo, “Structural Performance of Fiber-Reinforced Cementitious

Composite Members Reinforced with Fiber-Reinforced Polymer Bars: A Systematic Review," *Appl. Sci.*, vol. 15, no. 14, p. 7681, Jul. 2025, doi: 10.3390/app15147681.

[25] Y. H. Mugahed Amran, R. Alyousef, R. S. M. Rashid, H. Alabduljabbar, and C.-C. Hung, "Properties and applications of FRP in strengthening RC structures: A review," *Structures*, vol. 16, pp. 208–238, Nov. 2018, doi: 10.1016/j.istruc.2018.09.008.

[26] K. Soudki and T. Alkhrdaji, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-02)," in *Structures Congress 2005*, Reston, VA: American Society of Civil Engineers, Apr. 2005, pp. 1–8. doi: 10.1061/40753(171)159.

[27] M. Z. Naser, R. A. Hawileh, and J. A. Abdalla, "Fiber-reinforced polymer composites in strengthening reinforced concrete structures: A critical review," *Eng. Struct.*, vol. 198, p. 109542, Nov. 2019, doi: 10.1016/j.engstruct.2019.109542.

[28] T. Alkhrdaji, "Strengthening of concrete structures using FRP composites," *Struct. Mag.*, vol. 12, pp. 18–20, 2015.

[29] E. Ghafoori, M. Motavalli, A. Nussbaumer, A. Herwig, G. S. Prinz, and M. Fontana, "Design criterion for fatigue strengthening of riveted beams in a 120-year-old railway metallic bridge using pre-stressed CFRP plates," *Compos. Part B Eng.*, vol. 68, pp. 1–13, Jan. 2015, doi: 10.1016/j.compositesb.2014.08.026.

[30] *Recommended Construction Specifications and Process Control Manual for Repair and Retrofit of Concrete Structures Using Bonded FRP Composites*. Washington, D.C.: Transportation Research Board, 2008. doi: 10.17226/23116.

[31] M. Fossetti, G. Minafò, and M. Papia, "Flexural behaviour of glulam timber beams reinforced with FRP cords," *Constr. Build. Mater.*, vol. 95, pp. 54–64, Oct. 2015, doi: 10.1016/j.conbuildmat.2015.07.116.

[32] K.-U. Schober, A. M. Harte, R. Kliger, R. Jockwer, Q. Xu, and J.-F. Chen, "FRP reinforcement of timber structures," *Constr. Build. Mater.*, vol. 97, pp. 106–118, Oct. 2015, doi: 10.1016/j.conbuildmat.2015.06.020.

[33] S. A. Hadigheh, R. McDougall, C. Wiseman, and L. Reid, "Evaluation of composite action in cross laminated timber-concrete composite beams with CFRP reinforcing bar and plate connectors using Digital Image Correlation (DIC)," *Eng. Struct.*, vol. 232, p. 111791, Apr. 2021, doi: 10.1016/j.engstruct.2020.111791.

[34] B. Li, J. Zhang, X. Zhou, and G. Du, "Effects on the protection of bamboo by cold plasma and 2D resin-based protective agent.," 2021.

[35] T. C. Triantafillou, "Strengthening of structures with advanced FRPs," *Prog. Struct. Eng. Mater.*,

vol. 1, no. 2, pp. 126–134, Jan. 1998, doi: 10.1002/pse.2260010204.

[36] G. Fava, V. Carvelli, and C. Poggi, "Pull-out strength of glued-in FRP plates bonded in glulam," *Constr. Build. Mater.*, vol. 43, pp. 362–371, Jun. 2013, doi: 10.1016/j.conbuildmat.2013.02.035.

[37] G. M. Raftery and A. M. Harte, "Nonlinear numerical modelling of FRP reinforced glued laminated timber," *Compos. Part B Eng.*, vol. 52, pp. 40–50, Sep. 2013, doi: 10.1016/j.compositesb.2013.03.038.

[38] J. Vessby, E. Serrano, and B. Enquist, "Contact-free measurement and numerical and analytical evaluation of the strain distribution in a wood-FRP lap-joint," *Mater. Struct.*, vol. 43, no. 8, pp. 1085–1095, Oct. 2010, doi: 10.1617/s11527-009-9568-x.

[39] S. Kramár, M. Brabec, P. Pařil, R. Rousek, and P. Král, "Constraining delamination of CFRP by beam corrugation," *Eng. Struct.*, vol. 207, p. 110237, Mar. 2020, doi: 10.1016/j.engstruct.2020.110237.

[40] Y. Yang, J. Liu, and G. Xiong, "Flexural behavior of wood beams strengthened with HFRP," *Constr. Build. Mater.*, vol. 43, pp. 118–124, Jun. 2013, doi: 10.1016/j.conbuildmat.2013.01.029.

[41] F. A. Fathelbab, M. S. Ramadan, and A. Al-Tantawy, "Strengthening of RC bridge slabs using CFRP sheets," *Alexandria Eng. J.*, vol. 53, no. 4, pp. 843–854, Dec. 2014, doi: 10.1016/j.aej.2014.09.010.

[42] A. Belarbi and B. Acun, "FRP Systems in Shear Strengthening of Reinforced Concrete Structures," *Procedia Eng.*, vol. 57, pp. 2–8, 2013, doi: 10.1016/j.proeng.2013.04.004.

[43] M. Chellapandian and S. Suriya Prakash, "Behavior of FRP-Strengthened Reinforced Concrete Columns Under Pure Compression—Experimental and Numerical Studies," 2019, pp. 663–673. doi: 10.1007/978-981-13-0365-4_56.

[44] L. Bisby and M. Ranger, "Axial–flexural interaction in circular FRP-confined reinforced concrete columns," *Constr. Build. Mater.*, vol. 24, no. 9, pp. 1672–1681, Sep. 2010, doi: 10.1016/j.conbuildmat.2010.02.024.

[45] C. E. Bakis *et al.*, "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures," *Rep. by ACI Comm.*, vol. 440, no. 2002, pp. 1–45, 2002.

[46] M. Zarringol and M. Zarringol, "A comparative study on the efficiency of CFRP and GFRP in the improvement of compressive strength, acoustic impedance and bracing of filled and hollow concrete columns in different layers and ages," *J. Sustain. Dev.*, vol. 9, no. 5, p. 110, 2016.

[47] D. O. Owolabi, M. Shokouhian, I. Ahmad, M. Jenkins, and G. L. McLemore, "Comparative Analysis of Autogenous and Microbial-Based Calcite Precipitation in Concrete: State-of-the-Art Review," *Buildings*, vol. 15, no. 18, p. 3289, Sep. 2025, doi: 10.3390/buildings15183289.

[48] L.-Z. Yao and G. Wu, "Fiber-Element Modeling for Seismic Performance of Square RC Bridge

Columns Retrofitted with NSM BFRP Bars and/or BFRP Sheet Confinement," *J. Compos. Constr.*, vol. 20, no. 4, Aug. 2016, doi: 10.1061/(ASCE)CC.1943-5614.0000652.

[49] T. M. Pham and H. Hao, "Review of Concrete Structures Strengthened with FRP Against Impact Loading," *Structures*, vol. 7, pp. 59–70, Aug. 2016, doi: 10.1016/j.istruc.2016.05.003.

[50] S. Babaeidarabad, G. Loreto, and A. Nanni, "Flexural Strengthening of RC Beams with an Externally Bonded Fabric-Reinforced Cementitious Matrix," *J. Compos. Constr.*, vol. 18, no. 5, Oct. 2014, doi: 10.1061/(ASCE)CC.1943-5614.0000473.

[51] T. El Maaddawy and K. Soudki, "Carbon-Fiber-Reinforced Polymer Repair to Extend Service Life of Corroded Reinforced Concrete Beams," *J. Compos. Constr.*, vol. 9, no. 2, pp. 187–194, Apr. 2005, doi: 10.1061/(ASCE)1090-0268(2005)9:2(187).

[52] N. Attari, S. Amziane, and M. Chemrouk, "Flexural strengthening of concrete beams using CFRP, GFRP and hybrid FRP sheets," *Constr. Build. Mater.*, vol. 37, pp. 746–757, Dec. 2012, doi: 10.1016/j.conbuildmat.2012.07.052.

[53] L. de Waal, D. Fernando, V. T. Nguyen, R. Cork, and J. Foote, "FRP strengthening of 60 year old pre-stressed concrete bridge deck units," *Eng. Struct.*, vol. 143, pp. 346–357, Jul. 2017, doi: 10.1016/j.engstruct.2017.03.062.

[54] G. Camata, E. Spacone, R. Al-Mahaidi, and V. Saouma, "Analysis of Test Specimens for Cohesive Near-Bond Failure of Fiber-Reinforced Polymer-Plated Concrete," *J. Compos. Constr.*, vol. 8, no. 6, pp. 528–538, Dec. 2004, doi: 10.1061/(ASCE)1090-0268(2004)8:6(528).

[55] S. . Smith and J. . Teng, "FRP-strengthened RC beams. I: review of debonding strength models," *Eng. Struct.*, vol. 24, no. 4, pp. 385–395, Apr. 2002, doi: 10.1016/S0141-0296(01)00105-5.

[56] A. A. Mutalib and H. Hao, "Numerical Analysis of FRP-Composite-Strengthened RC Panels with Anchorages against Blast Loads," *J. Perform. Constr. Facil.*, vol. 25, no. 5, pp. 360–372, Oct. 2011, doi: 10.1061/(ASCE)CF.1943-5509.0000199.

[57] H. M. Elsanadedy, T. H. Almusallam, S. H. Alsayed, and Y. A. AL-Salloum, "Experimental and FE study on RC one-way slabs upgraded with FRP composites," *KSCE J. Civ. Eng.*, vol. 19, no. 4, pp. 1024–1040, May 2015, doi: 10.1007/s12205-013-0689-y.

[58] J. G. Teng, J. F. Chen, S. T. Smith, and L. Lam, "Behaviour and strength of FRP-strengthened RC structures: a state-of-the-art review," *Proc. Inst. Civ. Eng. - Struct. Build.*, vol. 156, no. 1, pp. 51–62, Feb. 2003, doi: 10.1680/stbu.2003.156.1.51.

[59] W. Chen, T. M. Pham, H. Sichembe, L. Chen, and H. Hao, "Experimental study of flexural behaviour of RC beams strengthened by longitudinal and U-shaped basalt FRP sheet," *Compos. Part B Eng.*, vol. 134, pp. 114–126, Feb. 2018, doi: 10.1016/j.compositesb.2017.09.053.

[60] ABET, "abet.org." [Online]. Available: www.abet.org

[61] D. A. Kolb, *Experiential learning: Experience as the source of learning and development*. FT press, 2014.

[62] K. Campus and S. Penrith, “Engineering education - is problem-based or project-based learning the answer?,” *Australas. J. Eng. Educ.*, vol. 3, p. ISSN 1324-5821, 2003, [Online]. Available: http://www.aaee.com.au/journal/2003/mills_treagust03.pdf

[63] T. Siregar, “Effectiveness of the Problem-Based Learning Model in Improving Students’ Mathematical Communication Skills and Learning Motivation,” Oct. 20, 2025. doi: 10.20944/preprints202510.1562.v1.

[64] L. W. Anderson and D. R. Krathwohl, *A taxonomy for learning, teaching, and assessing: A revision of Bloom’s taxonomy of educational objectives: complete edition*. Addison Wesley Longman, Inc., 2001.

[65] L. W. Anderson and D. R. Krathwohl, “Anderson and Krathwohl Bloom’s Taxonomy Revised .pdf,” 2016. [Online]. Available: https://www.quincycollege.edu/wp-content/uploads/Anderson-and-Krathwohl_Revised-Blooms-Taxonomy.pdf

[66] M. Prince, “Does active learning work? A review of the research,” *J. Eng. Educ.*, vol. 93, no. 3, pp. 223–231, 2004, doi: 10.1002/j.2168-9830.2004.tb00809.x.

[67] L. Breslow, C. White, and D. Hastings, “An International Study of the Teaching and Learning of Communication: Investigating Changes in Self-Efficacy in Four Undergraduate Engineering Programs,” in *2016 ASEE Annual Conference & Exposition Proceedings*, ASEE Conferences. doi: 10.18260/p.26223.