Encased Pultruded GFRP Beams with Shear Connectors: A Review

Abbas A. Allawi
Department of Civil Engineering, University of Baghdad, 17001, Baghdad, Iraq
A.Allawi@uobaghdad.edu.iq (corresponding author)

Teghreed H. Ibrahim
Department of Civil Engineering, University of Baghdad, 17001, Baghdad, Iraq
tagreed.hassan@coeng.uobaghdad.edu.iq

Enas M. Mahmood
Department of Civil Engineering, University of Baghdad, 17001, Baghdad, Iraq
e.mahmood1901p@coeng.uobaghdad.edu.iq

Tiba Hani Saadi
Department of Civil Engineering, University of Baghdad, 17001, Baghdad, Iraq
tibahani@coeng.uobaghdad.edu.iq

Mohammed Riyadh Khalaf
Department of Civil Engineering, University of Baghdad, 17001, Baghdad, Iraq
m.khalaf1101@coeng.uobaghdad.edu.iq

Hussein K. Mohammed
Iraqi Ministry of Higher Education and Scientific Research, Iraq
coffices@mohesr.gov.iq

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ABSTRACT

This study examines the structural performance of concrete-encased pultruded Glass Fiber Reinforced Polymer (GFRP) I-sections with shear connections. It specifically focuses on how different parameters affect the latter's ductility, flexural strength, and load-carrying capacity. The key variables studied include various shear connector types, spacing, and geometries, as well as the compressive strength of concrete and the properties of GFRP. The finite element modeling and experimental validation show that the shear connectors significantly improve the ductility, ultimate capacity, and load transmission efficiency. The present review emphasizes that the shear connectors greatly enhance the structural performance when they are properly used. The long-term durability and failure modes must also be considered. For instance, having reduced the connector spacing from 375 mm to 100 mm increased the ultimate load by up to 34.5% in some cases, while having increased the concrete compressive strength from 30 MPa to 53.8 MPa led to a notable improvement in the flexural stiffness.

Keywords- pultruded GFRP profile; encased beam; shear connectors

I. INTRODUCTION

There are numerous applications for the Fiber Reinforced Polymer (FRP) materials in civil engineering, such as bridges, cooling towers, and buildings. Such materials are also used in new structures, like culverts [1, 2]. As an alternative to traditional materials like steel, the FRP materials, especially the GFRP pultruded profiles, are increasingly employed in civil engineering projects. The FRP buildings are gaining popularity, particularly in corrosive environments, due to their enhanced durability, lower maintenance requirements, high strength, lightweight nature, and low thermal conductivity [3-5]. FRP composites come in various forms, such as GFRP, Carbon Fiber Reinforced Polymer (CFRP), and Basalt Fiber

Reinforced Polymer (BFRP). Among these, CFRP has superior mechanical properties, including fatigue, resistance, and creep. However, its higher cost limits its use in many engineering applications [6]. GFRP and BFRP offer good mechanical properties and reasonable material costs but are more vulnerable to the chemical deterioration, especially in alkaline environments, which can limit their long-term performance [7]. Encasing GFRP profiles with concrete can improve their durability over time. The benefits of encased beams include enhanced ductility, reduced weight and deformation of structures, and increased strength capacity and stiffness. This approach also helps prevent the buckling in pultruded GFRP profiles [8]. Additionally, concrete-encased GFRP profiles improve the fire resistance in GFRP beams, making the encased beam suitable for various civil engineering projects, such as buildings, marine structures, and bridges [9]. The effects of GFRP bars and profiles on beams have been thoroughly investigated. The results show that the GFRP rebars consistently increase the tension capacity until failure, demonstrating that GFRP strengthens the hybrid beams and enables them to resist torsion [5]. GFRP is pultruded uniaxially during the production process. However, transverse loading is complex for this kind of pultruded GFRP. For the improvement of the pultruded GFRP's behavior, concrete is used with GFRP to produce composite sections. Like pultruded, concrete-filled tubes [10], encased pultruded GFRP with concrete. Unlike previous studies that primarily investigated either the flexural behavior or the connection detailing, this review bridges this gap by correlating the shear connector geometry and positioning with the global beam performance, particularly in under-researched configurations, such as dual-sided connectors [11]. Moreover, this study integrates the findings from both experimental and numerical works, offering a comprehensive understanding of the mechanical interaction between the pultruded GFRP beams and surrounding concrete. The review highlights areas that lack in-depth exploration, such as long-term durability and slip modeling under partial interaction conditions.

II. PULTRUDED GLASS FIBER REINFORCED POLYMER PROFILE

Pultruded profiles are the most widely used method for producing GFRP load-bearing components among the various methods available. Standard GFRP cross-sections are pultruded to resemble steel structures. More complex multicellular designs are also available for building bridge decks employing adhesive bonding, as shown in Figure 1.

FRP consists of multiple components: reinforcing fibers, a matrix for shear transfer, and additional fillers or additives. The continuous fibers serve as the primary load-bearing element, while the matrix transfers shear stress, bonds the fibers, and protects them. The pultruded FRP members are widely used due to the efficiency of the pultrusion process, which offers low labor cost, minimal material waste, and high production rates [11]. As depicted in Figure 2 [12], the process involves aligning fiber reinforcements (rovings or fabrics), passing them through a resin bath containing catalysts, accelerators, fillers, and wetting agents, and then pulling the saturated reinforcements through a heated die for curing. Once cured, the rigid composite member is cut to the desired length. The pultruded GFRP profiles are lightweight, strong, and stiff, with excellent durability in aggressive environments, corrosion resistance, low thermal conductivity, and adaptable shapes, making them increasingly popular in structural engineering applications.

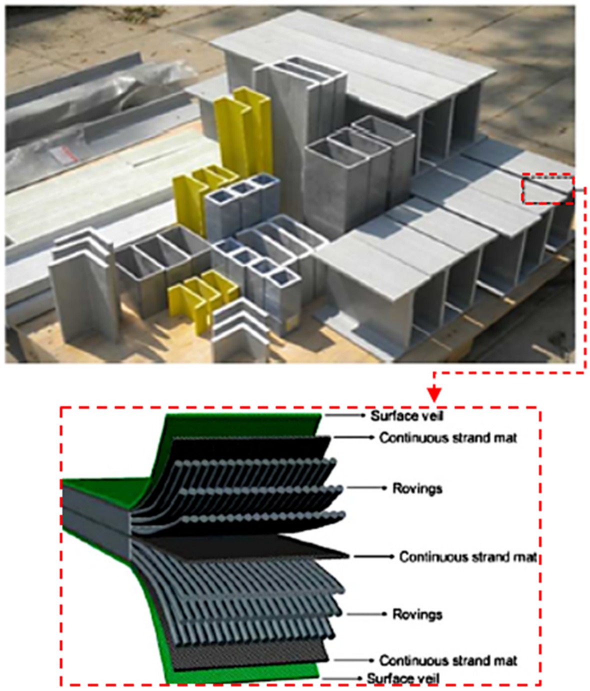


Fig. 1. Pultruded profiles and fiber-matrix architecture.

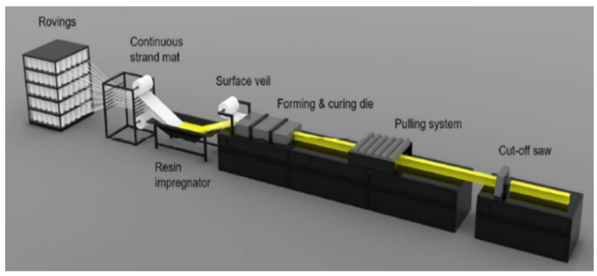


Fig. 2. Pultruded process.

III. COMPOSITE SECTION TYPES

The pultruded GFRP profiles are appropriate for the GFRP structures. Additionally, they are employed with various materials to create hybrid members. Three kinds of composite beams are displayed in Figure 3.

- Composite beam: It contains a concrete block above a pultruded I-beam, as presented in Figure 3 (a). The pultruded GFRP beam is utilized for tension stress, whereas the concrete on top is intended for compression stress; the disadvantage of this type is the web instability that is not disregarded during the application of load. Additionally, the resistance of the pultruded beam to fire is weak because the I-section beam is exposed to air without protection [13].

- Encased beam: The pultruded GFRP beam embedded in the middle of the concrete cross-section, as shown in Figure 3 (b). Comparing the encased beam with the first type, it is observed that the stability and the fire resistance were improved in e-beams [14, 15]. However, this composite beam fails in a brittle manner because GFRP and concrete have low ductility. However, the ductility can be increased by encasing pultruded GFRP in reinforced concrete.
- Concrete-filled GFRP tube: This is made by casting concrete inside a box-shaped structure, as portrayed in Figure 3 (c). The GFRP tube section, which may be utilized as formwork and supplies flexural stiffness and strength, is an additional advantage of this composite beam, reducing the construction costs and duration.

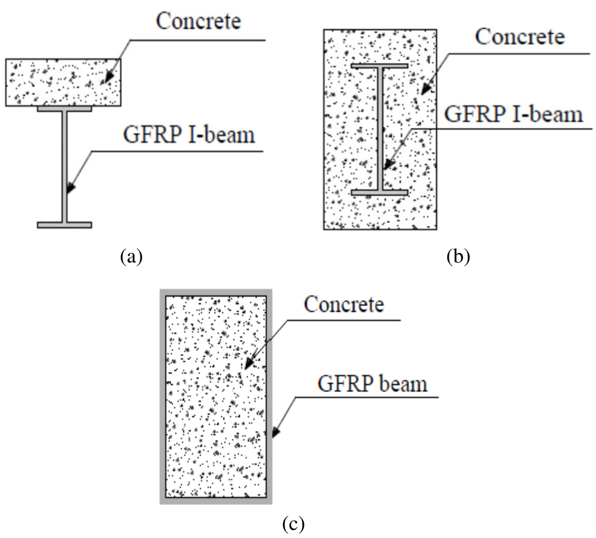


Fig. 3. Types of composite beams: (a) composite section, (b) encased pultruded GFRP beam, (c) concrete-filled GFRP tube.

IV. ENCASED PULTRUDED GFRP BEAM

Hybrid beams consist of Reinforced Concrete (RC) members mechanically attached to pultruded GFRP profiles, making them suitable for applications, such as building floors, footbridges, and marine pier superstructures [15]. This composite system is designed to combine the advantages of both materials while mitigating their individual limitations. In such beams, the GFRP profile primarily resists the shear and tensile forces, while the surrounding concrete provides compression resistance and stabilizes the top element. To reduce costs, commonly available pultruded sections are used, and concrete is incorporated to improve ductility. Because of this composite configuration, particular attention has been given to the mechanical connection between the concrete and the GFRP beam. The choice of the shear connector types and their spacing has been based on [14, 16, 17], where it was demonstrated that the connector spacing significantly influences the load distribution and slip behavior [18]. Likewise, the variations in concrete compressive strength have been studied due to their effect on the ductility and stiffness [5]. Encasing the GFRP beam has often been implemented with a low degree of shear connection [17]. Previous research has also proposed reinforcing encased I-beams to address the bond slip and ductility issues commonly observed in FRP-RC members [14]. In broader practice, an "encased beam" refers to a steel beam surrounded by concrete, treated as a homogeneous composite member and analyzed using elastic theories, like conventional RC design assumptions [19]. For the pultruded GFRP I-sections, the shear connectors are typically placed along the flanges to prevent the slippage between the concrete and the beam. The degree of interaction, partial or full, depends on the connectors' size, welding, and spacing [20]. When shear connectors ensure full interaction, the encased structure behaves as a single unit with negligible slip, leading to greater stiffness and improved performance [21]. In contrast, partial interaction is characterized by maximum slippage near the beam ends and minimal slip at mid-span [20].

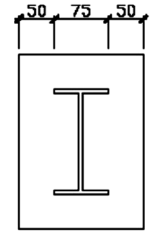
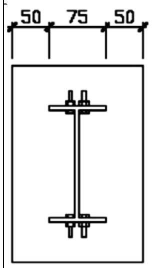
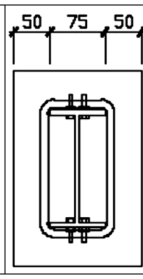
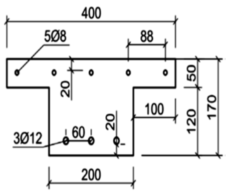
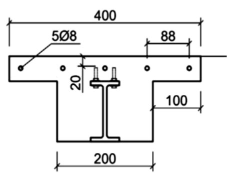
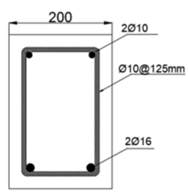
V. CONNECTION OF FRP PROFILES

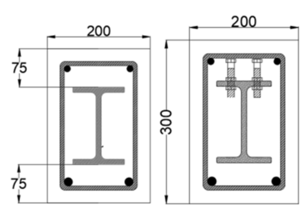
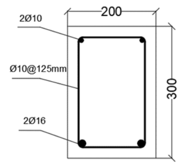
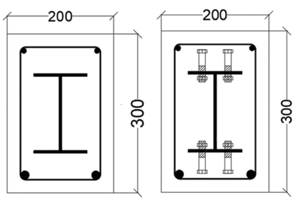
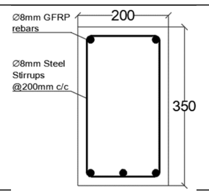
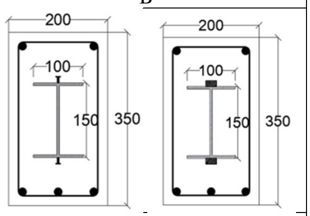
The pultruded GFRP profiles offer notable advantages, such as building material, including a high strength-to-weight ratio and adaptability; however, one of the main challenges in their structural application lies in the connection design. Properly designed connections are essential to ensure a reliable structural performance. While several design guidelines exist for the steel frames, specifying welds or bolt arrangements, GFRP connections cannot be directly treated the same way. Although some GFRP connection designs borrow from the steel guidelines due to structural similarities, the inherent material properties of FRP differ significantly from those of steel, requiring the development of distinct design approaches [22]. Many studies have investigated the influence of the geometric parameters on the connection performance, such as plate thickness, the ratio of width to hole diameter, and the ratio of end distance to hole diameter [23]. The results showed that when the end distance-to-hole diameter ratio exceeded 1.5, its effect on the failure strength was minimal, whereas increasing the width-to-hole diameter ratio significantly enhanced the ultimate connection resistance. Additionally, finite element simulations in [11] modeled the concrete GFRP interface using nonlinear contact definitions, such as cohesive elements or contact pairs, to capture the slip behavior and evaluate the partial versus full interaction modes [24, 25].

VI. SUMMARY OF PREVIOUS STUDIES

A summary of previous studies is provided in Table I, including the properties and details of specimens, such as dimensions, type of support and loading, concrete compressive strength, and stirrup presence. The last column shows each study's results and a comparison of specimens with and without using shear connectors.

TABLE I. SUMMARY OF PREVIOUS STUDIES

Reference	Properties of specimens	Cross-section details	Discussion
[14]	Length: 1500 mm. Compressive strength: 71.78 MPa. Simply supported beams under 4-point load. Links and studs: set up at a distance of 100 mm at the top and bottom flange center to center.	 Plain	The use of studs enhanced the composite action between the pultruded GFRP I-section beam and the surrounding concrete, resulting in an increase in the ultimate load capacity. The beams with studs achieved approximately 13.8% higher peak loads compared to the plain beam, while the addition of both links and studs further improved the ultimate load by about 34.5% over the plain beam.
		 Stud  Link/Stud	Adding links and studs to the encased GFRP I-beam enhanced the ultimate load by 18.2% more than the beam with studs. The major failure mode was shear failure, which was distinguished by diagonal cracks propagating upward and joining at the top flange, particularly in specimens without shear reinforcement. Reinforcements, such as studs and links helped to control the fracture propagation but did not completely prevent the shear failure, which resulted in rupture under heavy loads.
[17]	Length: 2000 mm. Compressive strength: 30 MPa and 35 MPa. Simply supported beams under 3-point load. Stirrups: used at conventional RC M0.	 M0  M1	The hybrid specimens exhibited an ultimate load capacity approximately 50% greater than that of the conventional RC beam. However, their flexural stiffness was lower, primarily due to the relatively low elastic modulus of the pultruded GFRP material and the limited degree of partial interaction. Increasing the concrete compressive strength improved both the ultimate load capacity and stiffness, although the overall behavior remained constrained by the shear deformation capacity of the pultruded GFRP beam. For the conventional RC beam, the failure occurred in a ductile manner, beginning with the yielding of the tensile steel reinforcement and followed by concrete crushing in the compression zone. In contrast, the hybrid beam failed in a more brittle manner: the failure was initiated with concrete crushing at mid-span in the compression region, and shortly afterward, the bottom flange of the pultruded GFRP beam was suddenly separated from the web. This brittle failure was attributed to the increasing shear stresses concentrated at the web–flange connections and at the ends of the pultruded beam.
[26]	Length: 3000 mm. Compressive strength: 23.43 MPa. Simply supported beams under 3-point load. Shear connectors: installed at the top flange with a spacing of 375 mm from center to center. Stirrups: installed at a	 NR	The ultimate loads of the tested beams with GFRP were 51% and 65% for the specimens CG and CGC, respectively, compared to NR. The beam with shear connectors, CGC, increases the ultimate load by 9.5% compared to the composite specimen without shear connectors, CG. The ductility of the CG beam improves by 10.8% when compared to NR. The composite beams failed due to the delamination and longitudinal shear failure of the GFRP beam's web.

	spacing of 125 mm from center to center. The reference beam (NR) is a conventional RC beam without pultruded GFRP.	 CG CGC	
[11]	Length: 3000 mm. Compressive strength: 53.8 MPa. Simply supported beams under 3-point load. Shear connectors were installed on the top and bottom flanges with a spacing of 375 mm from center to center. Stirrups were installed at a distance of 125 mm from center to center. The reference beam (Ref) is a conventional RC beam without pultruded GFRP.	 Ref  EG EGS	The ultimate load capacity of the beams with a GFRP profile only (EG) and with both GFRP and shear connectors (EGS) increased by 58.3% and 100.6%, respectively, compared to the reference beam. Furthermore, the EGS beam achieved a 26.7% higher ultimate load than the EG beam, demonstrating the effectiveness of the shear connectors. The addition of the shear connectors also improved the ductility of the encased GFRP beams. Ref failed through the yielding of the tensile reinforcement, followed by the crushing of the concrete in the compression zone. As the loading progressed, multiple cracks developed through the depth of the concrete section, and eventually, the tensile steel rebars ruptured, splitting the beam into two parts. In the encased beams (EG and EGS), cracks were initiated at the mid-span and propagated toward the compression zone. After reaching the ultimate load, major cracks were merged, and shear cracks were formed. The final failure was characterized by concrete crushing, spalling of the cover, and buckling of the top steel rebars, followed by rupture of both the GFRP beams and the bottom steel rebars.
[5]	The specimen had a length of 3000 mm and a concrete compressive strength of 30 MPa. It was tested as a simply supported beam under a 4-point loading setup. Shear studs and C-channels were installed at 200 mm spacing, applied to either one or both surfaces. The stirrups were also placed at 200 mm spacing, and the reinforcement included five GFRP rebars, each with a diameter of 8 mm. For comparison, the reference beam (Ref) was a conventional RC beam without a pultruded GFRP profile.	 B  BSEB BCEB	The composite beams with shear studs, BSEB, and C-channels, BCEB, exhibited a 22% increase in the ultimate load compared to the reference beam B. The GFRP rebars showed a steady increase in the tensile strain until failure, strengthening the beams. The encased GFRP I-section beams (BSTB and BCTB) improved the load capacity by ~20% and 18.18%. Adding shear connectors to both sides increased the load capacity by ~22%. The shear connectors improved the shear resistance and prevented the slip. Using connectors on both sides reduced the deflection by 18–22%, enhancing the stability. All tested beams eventually failed in flexure. The failure sequence typically included the yielding of the GFRP tension rebars, crushing of concrete in the compression zone, and formation of shear cracks in the shear span.

VII. CONCLUSIONS

- Using encased pultruded Glass Fiber Reinforced Polymer (GFRP) enhanced the properties of conventional Reinforced Concrete (RC) by about 50%.
- The load-carrying capacity of the encased beam was raised to 26.7% using shear connectors for connecting the concrete and pultruded GFRP beam.
- The ductility of the encased beam with shear connectors increased with the presence of tensile steel reinforcement.
- Utilizing shear connectors in encased beams had failure modes different from those of the conventional RC without a pultruded GFRP beam.

- Increasing the compressive strength of the specimen led to an improvement in the ultimate bending capacity and stiffness.
- GFRP-based hybrid beams with shear connectors offer sustainable, lightweight alternatives to conventional concrete, particularly in corrosive or fire-prone environments, with future research focusing on detailed modeling and connection optimization.

Overall, the integration of pultruded GFRP profiles with concrete offers a promising avenue for developing sustainable, durable, and high-capacity structural solutions. Future investigations should focus on enhancing the ductility, fire resistance, long-term durability under environmental exposure, fatigue, and seismic performance. Furthermore, standardized design codes should be established to facilitate the wider adoption of such profiles in structural engineering applications. However, previous research has not thoroughly explored the long-term behavior of connector-concrete interfaces under cyclic or environmental exposure. Additionally, quantitative models for predicting the partial interaction levels remain underdeveloped, indicating opportunities for future experimental and numerical investigation.

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